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INFLUENCE OF CHEMICAL COMPOSITION AND MICROSTRUCTURE ON THE TWO-BODY ABRASION RESISTANCE OF STEELS

Gilles Huard, ing., M.Sc.
Institut de génie des matériaux
CONSEIL NATIONAL DE RECHERCHES CANADA
75 boul. De Mortagne
Boucherville (Quebec) Canada J4B 6Y4

and

Prof. Dr. Karl-Heinz Habig
Bundesanstalt für Materialforschung und -prüfung (BAM)
Berlin, F.R.G.

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SUMMARY

Wear tests were carried out on plain carbon steels, chromium steels, chromium-molybdenum steels and tool steels using both flint and silicon carbide abrasive papers. The effect of hardness of the steels, their carbon content, their microstructure, their chromium-to-carbon atomic ratio as well as the hardness of the abrasive were considered. The results show that the influence of hardness varies greatly according to the nature of the abrasive particles. The wear resistance values of the alloy steels are mostly within the range of the carbon steels, except when the abrasive particles are too soft to cut the carbides in the tool steels. For a given heat treatment, the chromium steels usually exhibit a better relative wear resistance when the carbon content is low. The opposite is true with the chromium-molybdenum steels which have a better performance at higher carbon content.

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1. INTRODUCTION

The development of new materials which are resistant to abrasion contributes to lower the economic losses due to wear. A good comprehension of wear mechanisms is however necessary to achieve their elaboration. Although basic principles governing the abrasion of materials are well understood so that some general laws can be formulated, these are still rather empirical and each case of deterioration by wear remains specific to a particular tribosystem. More experiments are thus needed, which could help to reduce wear losses by increasing the existing knowledge of the wear behaviour of common materials, as well as through the development of new materials.

Two-body high-stress wear resistance experiments were carried out on chromium steels and chromium-molybdenum steels submitted to various heat-treatments such as normalizing, hardening and tempering. The values of resistance to wear by soft flint and hard silicon carbide abrasives were compared with those for plain carbon steels and tool steels similarly heat treated, as related to bulk hardness, carbon and alloying element contents and microstructure.

2. LITERATURE SURVEY

Early works showed that the wear resistance of a material could be related to its bulk hardness [1,2]. It was however observed that this latter parameter could not be used as the only indicator of resistance to abrasion since materials of equivalent hardness but of different types often exhibited different wear resistance values. Other experiments put forward the existence of several abrasion mechanisms. Microploughing, microcutting and spalling are three among the most important [3-5]. For ductile materials, microploughing would occur at low attack angles of abrasive particles while microcutting is prevalent at higher values [3]. The critical attack angle at which the change from predominantly microploughing to predominantly microcutting occurs was proved to vary with the properties of the materials being worn [4]. However, pure ploughing and pure cutting are not encountered in actual cases of

abrasion. Rather, when a hard particle scratches a surface, a certain amount of material is removed from the surface (microcutting) while the rest is pushed on each side of the groove (micro-ploughing). The proportion of each mechanism varies according to several properties of the material, for instance its capability of deformation [6]. Spalling is encountered mostly in brittle materials [5]. It is caused by microcracking of the surface or fracture of hard phase particles included in the material. In spite of the usually higher hardness of these materials, spalling often results in a larger amount of removed material and therefore in lower wear resistance.

Other experiments showed the abrasion resistance to be dependent on the hardness of abrasive particles [7] or, more exactly, on the ratio of the hardness of the abrasive to that of the material being worn. A low hardness ratio is associated with a low level of wear while a high ratio leads to a high level. The two levels are linked at intermediate values of hardness ratio by a region where the abrasion resistance is more sensitive to this parameter [8].

The microstructure of the tested materials is also a variable of importance, especially the presence of a second phase, its nature, amount, hardness and shape [9]. Plain carbon steels were among the first two-phase materials to be investigated from the point of view of the influence of microstructure on the wear resistance. Since their wear behaviour is now quite well known, they are often used as a reference to evaluate and understand the wear behaviour of more complex materials. An increase in carbon content of hypoeutectoid plain carbon steels leads to an increase of hardness and of abrasion resistance [10]. For a given hardness, the steel having a higher carbon content is usually more wear resistant [11]. The microstructures of carbon steels can be ranked roughly from the least to the most wear resistant as follows: tempered martensite, pearlite, martensite, bainite [12]. Such a ranking is however subject to modification when particular materials are tested.

High chromium white cast irons are often discussed in the literature

because of their extensive use in situations where an abrasion resistant material is needed. A point of particular interest of these studies is that the carbides included in the microstructures of these cast irons may exceed in hardness the minerals used as abrasive. No general correlation was found between the composition, the hardness and the abrasion resistance of high chromium white cast irons. Rather, the results were found to be strongly dependent on the test conditions [13]. It seems however that the carbide removal would be the controlling factor of the wear resistance of high chromium white cast irons [13-16]. When the abrasive is capable of causing spalling and pitting of carbides, the wear resistance decreases with an increase of carbide volume fraction. The nature of the surrounding matrix is not to be neglected. Experiments showed that when the matrix can be removed from the surface, the carbides become less protected and easier to be broken. This seems to be particularly true when the iron has a low amount of carbide allowing the abrasive to reach and deform the matrix. Also, it has been demonstrated that a softer austenite matrix could increase the wear resistance of an iron because of its work hardening under high stress abrasion against a relatively hard abrasive [13].

In contrast to what can be found in the literature about the wear properties of high chromium white cast irons, little information is available on steels with a small amount of chromium and molybdenum. The effect of various heat treatments on the wear resistance of Cr steels (approx. 1% Cr) and Cr-Mo steels (approx. 1% Cr and 0,2% Mo) was therefore investigated and compared to results obtained with a series of plain carbon steels and a few tool steels similarly heat treated.

3. EXPERIMENTAL METHOD

3.1 Materials

3.1.1 Chemical Composition

Plain carbon steels and steels containing different amounts of alloying

elements - mainly chromium and molybdenum - were selected for this study. The compositions are given in Table I. According to the official standards, they are classified into three main groups, namely cementation steels, heat-treatable steels, and tool steels. However, since the present work was being directed toward the effect of alloying elements and microstructures, the steels were divided into four groups following a somewhat different pattern.

The first group is that of hypoeutectoid plain carbon steels. The results of their tests were mainly used as a reference for the other materials since the relations between their composition, hardness, microstructure and wear resistance are quite well known.

The second group is formed by steels having compositions similar to the carbon steels but with chromium as the main alloying element. These are essentially the steels 28Cr4, 34Cr4 (AISI 5132) and 41Cr4 (AISI 5140), to which the steel 15Cr3 (AISI 5015) may be added. They will be called "chromium steels".

The third group is composed of steels having chromium and molybdenum as principal alloying elements: 16CrMo4, 25CrMo4, 34CrMo4 (AISI 4137), 42CrMo4 (AISI 4140), and 50CrMo4. They will be called "chromium-molybdenum steels". It is important to note that with these steels, the real influence of molybdenum alone cannot be distinguished and directly compared with that of chromium in the former group. Rather, the combined effect of chromium and molybdenum must be considered.

The last group consists of tool steels. Their compositions and microstructures are very different from the hypoeutectoid carbon steels and vary greatly, even within this group itself. Therefore, they can be compared only on an invidivual basis and general observations on their abrasion resistance are the only possible conclusions. This group includes the following steels: 100V1, (AISI W210), 90Cr3, 145Cr6, X210Cr12 (AISI D3) and S6-5-2 (AISI M2).

3.1.2 Heat treatments, microstructures and hardness

Normalizing, annealing and hardening with two different tempering temperatures were the heat treatments used to vary the hardness and the microstructure of the steels. Details are given below and summarized in Tables II, III and IV, together with the resulting hardness values and microstructures. Micrographs can be seen in Figures A1 to A48 of the Appendix.

The cementation steels were tested in the normalized condition. Their microstructure was a mixture of ferrite and pearlite.

The normalized condition was the as-received condition of the heat-treatable steels which had ferrite and pearlite as microstructure constituents. Bainite and martensite were also present to different extents in the as-received steels 34CrMo4 (AISI 4137), 42CrMo4 (AISI 4140), and 50CrMo4. All these steels were also hardened and tempered at two different temperatures in order to obtain two other types of microstructures. Tempered martensite was obtained after a tempering at 550°C for one hour. A similar heat treatment at 180°C (for 60 or 90 minutes) decomposes the tetragonal martensite into ε-carbides and cubic martensite and leaves the structure of retained austenite unchanged.

The tool steels were tested in two conditions: in the as-received annealed condition with microstructures of ferrite, globular cementite and special carbides, and after a hardening and tempering at 170°C (200°C for the steel X210Cr12) leading to various structures of martensite, retained austenite and special carbides.

Since the abrasion resistance of steels is often related to the hardness or the carbon content, it is interesting to visualize the relations between the last two parameters for the unalloyed and alloyed steels for all compositions and heat treatments (Figs 1 to 3). For a given group, an increase in carbon content usually corresponds to an increase in bulk

hardness. The addition of chromium increases the hardness of normalized steels and of steels hardened and tempered at 550°C, as compared to plain carbon steels. The molybdenum further increases the hardness. The influence of chromium and molybdenum changes when the steels are tempered at 180°C (Fig. 3). While both elements have no effect on the hardness of steels having more than 0,4% C, they slightly soften those containing less carbon. It is also to be noted that both the chromium steels and the chromium-molybdenum steels follow the same linear regression.

The tool steels were studied only in the as-received condition and following a hardening and tempering at 170°C. No relation exists between the bulk hardness and the carbon content, a situation which is normal in view of their different compositions and microstructures.

3.2 Abrasion tests

3.2.1 Description of the test method

The abrasion test rig is a "turn-table" type apparatus normally used for polishing. A schematic diagram is shown in Figure 4. The rotation speed (n_1) of the abrasive paper is 125 min^{-1} while that of the sample support (n_2) is 3 min^{-1} with respect to the eccentric axis. The annular shaped sample (42 mm O.D., 16 mm I.D.) is also free to rotate on its own symmetry axis. One of the main characteristics of this apparatus is that the sample passes several times on the same abrasive particles. Both flint and silicon carbide were used for the tests. The nominal grit diameter is 70 µm (paper grade 220) and the applied pressure was 0,019 N/mm^2. The test duration was 3 minutes per measurement and the wear resistance of each steel is the mean of usually four measurements on a unique specimen.

The quantities measured after each test were the weight loss of the sample (± 0,1 mg) and the thickness change at four different points (± 1 µm for each measurement). Figures 5 and 6 show the correlation between these two types of readings for various steels in the three heat treatment conditions

and abraded by flint and silicon carbide. The apparent larger scattering of results with the flint paper is due only to the scale of the graph.

The wear rate of a sample should usually be expressed by its volume loss since this quantity permits direct comparison of materials having different specific gravities. However, the thickness measurement device did not allow readings to be made on the exact same points after each test and led to an increased experimental error, as compared to the weight loss measurement, particularly for steels having a high wear resistance. Therefore, since the differences in specific gravity of the investigated steels are not large enough to result in misleading wear values, the weight loss was preferred for expressing them. Comparisons between graphs made with both measurements also showed that the use of thickness variations would not modify the trend of the results.

3.2.2 Correction for paper abrasiveness

Flint abrasive discs of a single batch were used to perform the tests and the abrasiveness is therefore approximately constant. On the other hand, two different batches of silicon carbide papers were used. A correction method to compensate for their different abrasiveness was established as follows.

Tests were carried out with both batches of silicon carbide abrasive paper on seven selected normalized samples. Figure 7 illustrates the correlation obtained between these two sets of results, listed in Table V. It is seen that the regression line intercepts the ideal situation of equal weight losses at a value of 110 mg. Since the weight loss ratio varies with the wear resistance value, the corrected weight losses were calculated by using the regression line appearing in Figure 7 instead of a constant mean ratio. For weight losses lower than 110 mg, no correction was made because it could be assumed that the paper from the batch I does not become less efficient than the other one, and consequently that both batches have a comparable abrasiveness.

The correction equations were then the following:

$$\Delta W_{SiC_I} = 1{,}4637 * \Delta W_{SiC_{II}} - 51{,}72 \qquad \text{if } \Delta W_{SiC_{II}} \quad 110 \text{ mg} \qquad (1)$$

$$\Delta W_{SiC_I} = \Delta W_{SiC_{II}} \qquad \text{if } \Delta W_{SiC_{II}} \quad 110 \text{ mg} \qquad (2)$$

where the mass losses are expressed in mg. The coefficient of correlation of equation (1) was evaluated at 0,99.

3.2.3 Relative wear resistance

The effect of alloying elements forming different types of carbide can be due partly to their influence on the bulk hardness but also to the interaction between individual carbides and abrasive particles. One question is what proportion of the total effect can be attributed to each of these causes. In order to eliminate the effect of undesired variations of the test conditions, the wear resistance is often presented in the form of a relative value expressed as the ratio of the weight loss of a standard specimen to that of the investigated material, both tested under the same overall conditions. In this calculation, the replacement of the wear resistance of a standard specimen by a standard relation between wear resistance and hardness should help to distinguish the role to be attributed to the individual "carbide-abrasive particle" interactions.

Though the cementite of hypoeutectoid plain carbon steels is much harder than ferrite, its presence in softer pearlite or as small particles greatly reduces its capability to resist the action of an abrasive particle. The wear mechanisms will not vary significantly with the carbon content and, to a first approximation, the increase of wear resistance with increasing carbon may be attributed to the effect of hardness [17]. Consequently, the relation between their absolute wear resistance (the inverse of their weight loss in grams) and the hardness (HV10) has been considered as the "standard value".

The relative wear resistance of an alloy steel was then expressed as the ratio of its own absolute wear resistance to that of plain carbon steel of equal hardness, both tested under the same conditions and after the same heat treatment. The linear regression equations for the wear resistance of plain carbon steels have been used for the calculations. For example, if the relation $W^{-1} = m_1 H + b_1$ was found for the carbon steels after a given heat treatment and if an alloy steel, after the same heat treatment, has a Vickers hardness H_a and a wear resistance W_a^{-1}, its relative wear resistance value will be:

$$(R.W.R.)_a = \frac{W_a^{-1}}{m_1 H_a + b_1} \qquad (3)$$

A relative wear resistance value close to unity signifies that the change in wear resistance is mainly due to a hardness effect similar to that involved in the plain carbon steels, while the action of individual hard phases will lead to higher or lower values.

4. OVERVIEW ON THE RESULTS

Table VI gives the wear resistance values of carbon steels in the three heat treatment conditions when abraded by flint. Table VII is the equivalent table for the abrasion by silicon carbide. Figures 8 and 9 correspond to Tables VI and VII respectively. The two graphs are similar and agree with results published earlier [18]. At relatively low values of bulk hardness, the improvement of wear resistance with increasing hardness is small as compared to the whole range of hardness. For harder steels (hardened and tempered at 180°C), the influence of hardness is ten times higher. This region constitutes a transition from the level of low wear resistance to a constant high level. This constant level is actually not observed in these tests. The critical values of hardness at which the wear resistance starts to increase were estimated to be approximately 490 HV10 with flint and 410 HV10 with silicon carbide abrasive. They result from the intercept between two regression lines, one calculated for the normalized steels together with those

tempered at 550°C, the other for the specimens tempered at 180°C.

The results for the alloy steels are presented in the same way as for the plain carbon steels. Table VIII and Figure 10 include the wear resistance values obtained with flint while Table IX and Figure 11 summarize those with silicon carbide. The spread is much higher than for carbon steels since these alloy steels include several different microstructural phases leading to more complex mechanisms of wear. Consequently, the estimation of the critical hardness was not made by using linear regression but, rather, by drawing an approximate enveloping curve. In both cases (Figs. 10 and 11), the value lies between 450 HV10 and 475 HV10. It is to be noted that a plateau of maximum wear resistance seems to be reached. Although such an observation agrees well with the general theory, it may also be due to the selection of alloy steels and no definite conclusions can be inferred. These comments also hold for the apparent diminution of wear resistance shown by the harder steels when abraded by silicon carbide which may be related to a lower toughness of these materials. It certainly reveals the less efficient action of the hard phase that they contain in the protection of the matrix against hard abrasive particles.

Three alloy steels have wear resistance to flint which does not fit the general behaviour. These are the normalized X210Cr12, S6-5-2 and 145Cr6 steels (the latter to a lesser extent) which all contain carbides capable of resisting the action of this relatively soft abrasive because of their quantity, hardness and size.

The similarity between the four cases of steel-abrasive combination is depicted in Figure 12. The main difference resides in the range of the resistance values, those for abrasion with flint being approximately ten times higher than those for abrasion with silicon carbide. This larger discrepancy as compared to results previously published [19] may be attributed to the nature of the tests. With the apparatus used for the present study, the procedure includes the action of used abrasive particles. Since the flint must undergo a more significant degradation than the silicon carbide, the

resulting values of wear resistance are substantially increased.

5. DETAILED ANALYSIS: RESULTS AND DISCUSSION

5.1 Carbon steels

The wear resistance of the carbon steels was plotted against the carbon content and the hardness values for each heat treatment and both abrasives. The effect of hardening and tempering at 550°C on the wear resistance to flint can be compared to that of normalizing in Figure 13. Figure 14 shows the similar graph for the abrasion with silicon carbide. Since the hardening and tempering at 180°C led to much higher wear resistance values, they were plotted separately (Fig. 15). Linear regressions were calculated for each case and the results are assembled in Table X.

Straight line equations describe quite well the inter-relations between the wear resistance, the bulk hardness, and the carbon content of the plain carbon steels. The use of either of the last two parameters as independent variable leads to equivalent coefficients of correlation. This was expected because of the linear relation between the hardness and the carbon content (see Figs 1 to 3).

The spread of results (Tables VIII and IX) may be considered as normal. The higher error of the tests with flint (about twice as much as with silicon carbide) may be due to a greater variation of the properties of the abrasive sheets or to a greater sensitivity of this abrasive to variations in the microstructures of steels. Such results were also noted for alloy steels.

For a given amount of carbon, the hardening and tempering at 550°C leads to higher bulk hardness but not necessarily to a higher wear resistance than normalized steels. Similar results were previously published [10]. This is particularly true for the abrasion with flint where the wear resistance is determined by the carbon content only (Fig. 13b). On the other hand, this heat treatment improves the wear resistance of low carbon steels to SiC (Fig.

14b) but to a level lower than that of a pearlitic steel of equivalent hardness (Fig. 14a).

5.2 Alloy steels

The results listed in Tables VIII and IX are displayed according to heat treatment in Figures 16 to 21. The dotted lines represent the linear regression for carbon steels. The values of chromium-to-carbon atomic ratio and of relative wear resistance are given in Table XI.

5.2.1 Chromium steels

No correlation is found between the hardness of the normalized chromium steels and their resistance to wear by flint (Fig. 16a). Since the hardness is linearly related to the carbon content (Fig. 1), no correlation holds between the wear resistance and the carbon content (Fig. 16b). From a general point of view, the wear resistance of these steels is not improved when compared to plain carbon steels of equivalent hardness, but they exhibit higher values on the basis of carbon content.

A strong relation exists, on the other hand, between the wear resistance to silicon carbide and the bulk hardness (Fig. 17a) or the carbon content (Fig. 17b). In this case, the alloy 41Cr4 is the only one with a value of relative wear resistance substantially higher than unity.

The addition of chromium to plain carbon steels shifts the pearlite point to a lower carbon concentration. In the normalized condition, the microstructure remains a mixture of ferrite and lamellar carbides, but the increased proportion of pearlite, as compared to plain carbon steels of equivalent carbon content (Figs A1 to A10), leads to a higher bulk hardness (Fig. 1).

The composition and the properties of the pearlite must be specific to each alloy since they should be influenced by the chromium content and the ratio of chromium to carbon. This is perhaps responsible for the lack of

correlation between the wear resistance to flint and the bulk hardness or the carbon content (Fig. 16). This is not so when the harder silicon carbide is used as abrasive since it can cut the hard phase of the steels (Fig. 17). Then the differences in the microstructures become a less important parameter.

The hardening and tempering of chromium steels at 550°C lead to a different wear behaviour. The wear resistance decreases with hardness or carbon content independently whether flint or silicon carbide is used as abrasive (Figs 18 and 19). These chromium steels are more wear resistant than the plain carbon steels, the difference becoming less as the bulk hardness (or carbon content) increases or when the softer abrasive is used. The resistance of the steel 41Cr4 abraded by flint is even lower than that of the plain carbon steel of equal hardness. These obervations are reflected by the values of relative wear resistance.

Relatively small quantities of carbide are formed in the lower carbon steels and the addition of chromium may modify their properties in such a way to greatly improve the wear resistance of the material. Since the amount of chromium remains approximately constant, the carbides formed in steels having a higher carbon content include a lower proportion of chromium. Thus, their properties move toward those of plain carbon steels, and so does the wear resistance. The lower values of relative wear resistance to flint, as compared to SiC, may be attributed to the hardness of this abrasive which is lower than that of the carbides contained in both types of steels, while the hardness of silicon carbide is higher than chromium carbide but lower than cementite.

The chromium steels hardened and tempered at 180°C exhibit a better resistance to wear by flint than the plain carbon steels of equivalent hardness (Fig. 20) or carbon content. However, an increase of the amount of carbon leads to a higher hardness but to a lower wear resistance, closer to that of plain carbon steels, which may be attributed to the lower Cr/C ratio. When the abrasive is silicon carbide, the three chromium steels have equal wear resistance values (Fig. 21), within the range of the carbon steels and

approximately ten times lower than when abraded by flint. Hence, a higher carbon content ratio has no favourable effect against this hard abrasive.

Another representation of the effect of chromium is given in Figure 22 where the relative wear resistance is plotted against the chromium-to-carbon atomic ratio. Except for the normalized steels abraded by silicon carbide, an increase of the Cr/C ratio induces an improvement of the relative wear resistance. Thus, an increase of the Cr/C ratio leads to carbides which better resist the action of the abrasive particles. This improvement of wear resistance will be greater against relatively soft abrasive.

The inverse relation observed for the normalized chromium steels abraded by silicon carbide has to be clarified. Such inversions of the influence of a parameter on the wear resistance were previously found in other tribosystems. It has been shown [8] that an increase of the amount of M_7C_3 carbides of martensitic CrMo white cast irons improves the resistance to abrasion by flint or alumina but has a negative effect against silicon carbide due to spalling. The higher Cr/C ratio of the normalized 28Cr4 steel may be responsible for a harder pearlite which better resists the action of flint, but which is also more easily cut by the hard silicon carbide because of a lower toughness. The relatively low amount of pearlite also enhances this phenomenon since the silicon carbide can penetrate deeper into the ferrite and be more capable of breaking the lamellar carbide.

5.2.2 Chromium-molybdenum steels

Wear tests on as-received chromium-molybdenum steels were carried out on only three alloys, namely the 34CrMo4, 42CrMo4 and 50CrMo4. The effect of hardness on the wear resistance to flint or silicon carbide is similar to that of plain carbon steels but the values are lower than expected from their hardness (Figs 16a and 17a). When one considers the carbon content, both the chromium-molybdenum steels and the carbon steels have comparable wear resistance values, except the steel 42CrMo4 abraded by silicon carbide which exhibits a much higher value (Figs 16b and 17b). This result seems not to be

due to the experimental error since it also appears to a lower extent with flint.

The microstructures of these steels are complex mixtures of up to four different phases in different proportions (Figs A11 to A13; Table II). Thus, even if an incrase of their hardness induces an improvement of the wear resistance, a clear explanation remains difficult to offer. We may however mention that the presence of martensite in the alloys 42CrMo4 and 50CrMo4 probably contributes to a better wear resistance, while the ferrite in the latter may be responsible for its relatively lower performance despite its higher bulk hardness.

An increase in hardness or carbon content of chromium-molybdenum steels, hardened and tempered at 550°C, induces a strong improvement in their wear resistance to flint or silicon carbide (Figs 18 and 19). This influence is much more important than in the plain carbon steels. The anomaly shown by the alloys 16CrMo4 and 25CrMo4, particularly when abraded by silicon carbide, can be attributed to their ambiguous hardness values (see Fig. 2). This situation is rectified if the carbon content is used as independent variable (Figs 18b and 19b).

Two different microstructures are encountered in the Cr-Mo steels hardened and tempered at 550°C (Table III): bainite in the two low-carbon steels (16CrMo4 and 25CrMo4) and tempered martensite in the other three. The results show that this difference of microstructure does not really influence the wear resistance values which rather are related to the hardness (or more strictly to the carbon content).

For low-carbon steels, the addition of chromium and molybdenum probably leads to the formation of a hard phase with a high (Cr + Mo)/C ratio. In small quantity, this phase may not resist the action of individual abrasive particles. Consequently, the wear resistance to flint does not really improve by comparison to plain carbon steels with equivalent carbon content. For abrasion by silicon carbide, the effect is even unfavourable and the alloy

steels are less wear resistant than the plain carbon steels. Moreover, the increase of hardness is not sufficient to compensate the poor resistance of the carbides and the relative wear resistance values are in most cases lower than unity (Table XI). Keeping the amount of chromium and molybdenum constant and adding carbon increase the amount of hard phase leading to a higher protection of the matrix and to an improved wear resistance in spite of the lower (Cr + Mo)/C ratio.

The wear resistance of the chromium-molybdenum steels, hardened and tempered at 180°C, lies on two levels (Figs 20 and 21). The two low-carbon alloy steels (16CrMo4 and 25CrMo4) exhibit equal values of wear resistance within the range of the plain carbon steels. This observation holds for wear by both abrasives. The other three steels (34CrMo4, 42CrMo4 and 50CrMo4) show a strong improvement of wear resistance against flint. With this abrasive, the values are about ten times higher than the steels containing less carbon, even higher than those obtained with the chromium steels. They seem however not to be related to the bulk hardness. A similar behaviour is noted for the abrasion by silicon carbide except that the high value of wear resistance is constant for the three alloys and only twice as high as the value obtained with the steels 16CrMo4 and 25CrMo4.

The heat treatment applied to the steels 16CrMo4 and 25CrMo4 differs slightly from the one applied to the other three steels of the same series in the sense that they were quenched into oil instead of water. The resulting slower cooling rate allows the formation of bainite which may be responsible for the lower wear resistance, contrary to what was observed for the same steels tempered at 550°C.

Despite the apparent difference between the behaviour of the chromium steels and the chromium-molybdenum steels, both hardened and tempered at 180°C, a similitude is found if the relative wear resistance values are plotted against the Cr/C ratio. Figure 23a shows that in the case of abrasion by flint, the chromium-molybdenum steels with higher carbon contents follow the same curve as the chromium steels. The two steels which do not fit the

curve are those quenched into oil and containing bainite. Figure 23b displays the results obtained with silicon carbide as abrasive. The plot is roughly similar to that of Figure 23a with a general tendency for the curve for chromium-molybdenum steels to lie below that for the chromium steels. This accounts for the lower wear resistance of the former alloys as depicted in Figure 21 and reveals their lesser effectiveness in resisting the attack of hard abrasive particles. The smaller discrepancy of the results of the steels 16CrMo4 and 25CrMo4, which now almost fit the curve of the chromium-molybdenum steels, may be attributed to the higher hardness of the abrasive.

5.2.3 Tool steels

The values of wear resistance to flint of the annealed tool steels are displayed in Figure 16. The alloys X210Cr12 and S6-5-2 are missing on this graph because their wear resistances were too high to be included in a suitable manner. The relative wear resistance of the tool steels to flint is usually better than that of the other alloys investigated but the steels 90Cr3 and 100V1 have a lower wear resistance than expected from their carbon content (Fig. 16b). Notwithstanding the tendency of the harder materials to be more wear resistant, no real correlation is found between these two parameters or with the carbon content, nor between the relative wear resistance and the Cr/C ratio (when it applies). The steels 90Cr3 and 100V1 exhibit wear resistance values in the range of those of the normalized plain carbon steels although slightly higher than those having equivalent hardness. An improvement is shown by the steel 145Cr6 in which the amounts of carbon and chromium allow the formation of a higher quantity of carbide. The best performance is obtained by the alloy X210Cr12 because its microstructure includes many carbide particles of a size comparable to the scratch width that can resist the action of the soft flint. An excellent performance is also shown by the alloy S6-5-2 in which chromium, molybdenum, vanadium and tungsten are the main alloying elements. The formation of special carbides is mainly responsible for the wear resistance of this steel.

The situation is quite different in abrasion by silicon carbide and the

favourable effect of the carbides does not always appear (Fig. 17). The steels 90Cr3, 100V1 and 145Cr6 exhibit lower resistance values than the plain carbon steels. Even the performance of the alloy S6-5-2 is slightly lower than that of the plain carbon steels, a behaviour that may be partly attributed to the relatively small size of its carbide particles. The alloy X210Cr12 is the only annealed tool steel with a relative wear resistance higher than unity, although its value has considerably diminished. The size of its carbides surely contributes to this performance since they are pulled out only with difficulty by the abrasive particles and limit the removal of the matrix.

Only two tool steels were tested with flint after a tempering at 170°C. Figure 20 and Table XI show that the steel 90Cr3 has a poor relative wear resistance. On the other hand, the performance of the steel 145Cr6 may be attributed to its hardness since the relative value is only 1,07. The wear resistance of the four tool steels tested with silicon carbide can be seen in Figure 21. They exhibit the lowest values of relative wear resistance (Table XI) amont the alloys investigated. These results suggest that such heat treated tool steels may have a wear resistance comparable to that of plain carbon steels of the same hardness if the abrasive is relatively soft. When abraded by a harder abrasive, their lower capability of deformation leads to a poor performance even if their microstructures include carbide particles.

6. CONCLUSIONS

6.1 Carbon steels

For a given microstructure, the wear resistance of carbon steels increases with increasing hardness or carbon content.

The hardening and tempering at 550°C of a carbon steel increase its hardness as compared to the normalized structure containing the same amount of carbon but the wear resistance to flint remains unchanged. The wear resistance of low-carbon steels to silicon carbide improves a little after

such a heat treatment.

A stronger dependence of wear resistance to both flint and silicon carbide on the bulk hardness is observed if the steels are hardened and tempered at 180°C.

6.2 Chromium steels

Heat treatable steels containing 1% chromium usually show a better wear resistance than plain carbon steels with equal carbon content. At equivalent hardness, the chromium steels may exhibit a higher or a lower wear resistance than the plain carbon steels, depending on the tribosystem.

Under most test conditions, a decreasing wear resistance was observed with increasing hardness (or carbon content) of the chromium steels.

Except for the case of normalized chromium steels abraded by silicon carbide, an increase of the Cr/C atomic ratio induces an increase of the relative wear resistance. The latter was defined as the wear resistance of an alloy steel divided by that of the plain carbon steel of equal hardness and abraded under the same experimental conditions. The lower Cr/C ratio of steels containing higher carbon could therefore explain their lower wear resistance.

6.3 Chromium-molybdenum steels

The wear resistance of normalized heat treatable steels containing chromium (from 0,96% to 1,17%) and molybdenum (about 0,20%) increases with bulk hardness or carbon content. The relative wear resistance values are lower than unity and not dependent on the Cr/C ratio. This behaviour may be attributed by differences in microstructure.

Hardness (or carbon content) influences the wear performance more strongly in the Cr-Mo steels hardened and tempered at 550°C than in carbon

steels after the same heat treatment, but the effect is similar. The relative wear resistance values are lower than unity for the low-carbon alloy steels and become higher as the hardness increases. For these steels, an increase of the Cr/C ratio lowers the relative wear resistance but coincides with a decrease of the carbon content which may also be the explanation.

The presence of bainite after a hardening and a tempering at 180°C of chromium-molybdenum steels containing low carbon may explain the wear resistance values which are comparable to those of plain carbon steels of equal hardness. At higher carbon content, the microstructure consists of martensite and retained austenite and the resistance to wear by flint is increased as compared to carbon steels. However, their resistance to wear by silicon carbide was constant and poorer than that of plain carbon steels. With flint the relative wear resistance increases with increasing Cr/c ratio, with silicon carbide the Cr/C ratio is less important.

6.4 Tool steels

The hard carbides in tool steels are only effective if they cannot be cut by the abrasive, because of their hardness and size. Consequently, the wear resistance to flint was higher than that of the carbon steels, but comparable to them when silicon carbide was used as abrasive.

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Table I

Chemical composition of the investigated steels

Standards DIN	AISI	Chemical composition in wt. % C	Si	Mn	P	S	Cu	Cr	Ni	Mo	Nb	Ti	V	W	Al	Co	Sn
Cementation steels																	
C15	1015	0,20	0,23	0,56	0,013	0,018		0,013	0,02	0,007							
Ck22	(1020)	0,22	0,16	0,51	0,010	0,026	0,22	0,131	0,13	0,033					0,041	0,016	
15Cr3	5015	0,17	0,28	0,57	0,020	0,021	0,19	0,69	0,18	0,05					0,030		0,014
Heat-treatable steels																	
Ck22	(1020)	0,22	0,16	0,51	0,010	0,026	0,22	0,131	0,13	0,033					0,041	0,016	
Ck35	(1035)	0,36	0,22	0,63	0,011	0,014	0,05	0,104	0,05	0,011			0,003		0,018	0,013	
C45	1045	0,44	0,26	0,57	0,014	0,024	0,13	0,18	0,07	0,03					0,029		0,012
Ck53		0,55	0,29	0,68	0,017	0,027	0,20	0,14	0,07	0,04					0,032		0,013
C60	1060	0,60	0,31	0,76	0,010	0,031	0,20	0,13	0,09	0,03					0,003		0,013
28Cr4		0,27	0,12	0,79	0,010	0,030	0,11	0,94	0,15	0,045	0,001		0,002	0,009	0,029	0,022	
34Cr4	5132	0,31	0,30	0,80	0,024	0,029	0,09	0,98	0,07	0,018	0,001		0,002		0,052	0,010	
41Cr4	5140	0,42	0,30	0,60	0,015	0,030	0,20	0,98	0,12	0,03					0,044		0,013
16CrMo4		0,22	0,23	0,79	0,009	0,031	0,10	1,17	0,12	0,224	0,002	0,002	0,002	0,005	0,034	0,015	
25CrMo4		0,26	0,24	0,71	0,016	0,034	0,22	1,05	0,12	0,191	0,001	0,002	0,002	0,006	0,027	0,016	
34CrMo4	4137	0,34	0,19	0,68	0,014	0,025	0,15	1,06	0,22	0,200	0,002	0,003	0,002	0,005	0,032	0,016	
42CrMo4	4140	0,45	0,29	0,65	0,012	0,035	0,16	1,15	0,10	0,228	0,002				0,039	0,012	
50CrMo4		0,53	0,26	0,62	0,013	0,026	0,12	0,96	0,07	0,193	0,003	0,003		0,004	0,032	0,013	
Tool steels																	
90Cr3		0,91	0,28	0,33	0,016	0,013	0,12	0,77	0,08	0,023					0,026	0,009	
100V1	W210	0,99	0,17	0,203	0,007	0,016	0,04	0,154	0,05	0,019			0,099		0,018	0,006	
145Cr6		1,34	0,20	0,57	0,018	0,018	0,08	1,33	0,29	0,044	0,001	0,004	0,011		0,011	0,009	
X210Cr12	D3	2,03	0,25	0,48				11,8									
S 6-5-2	M2	0,95	0,44	0,298	0,037	0,015	0,24	4,0	0,31	5,0	0,021	0,012	1,8	6,5	0,77	4,0	

Table II

Heat treatments, hardness and microstructures of "as-received" steels

Designation	Heat treatment	Hardness HV10	Microstructures	Fig.
C15 (1015)	normalizing	137±1	Ferrite, pearlite	A1
Ck22 (1020)	normalizing	161±1	Ferrite, pearlite	A2
Ck35 (1035)	normalizing	179±3	Ferrite, pearlite	A3
Ck45 1045	normalizing	202±7	Ferrite, pearlite	A4
Ck53	normalizing	225±6	Ferrite, pearlite	A5
C60 (1060)	normalizing	242±4	Pearlite, with ferrite	A6
15Cr3 (5015)	normalizing	150±3	Ferrite, pearlite	A7
28Cr4	normalizing	189±1	Ferrite, pearlite	A8
34Cr4 (5132)	normalizing	208±3	Ferrite, pearlite	A9
41Cr4 (5140)	normalizing	251±1	Pearlite, with ferrite	A10
34CrMo4 (4137)	unknown	280±6	Ferrite, pearlite, bainite	A11
42CrMo4 (4140)	unknown	311±10	Pearlite, martensite	A12
50CrMo4	unknown	316±4	Ferrite, pearlite, bainite, martensite	A13
90Cr3	spheroidization	171±4	Ferrite, globular cementite	A14
100V1 (W210)	spheroidization	189	Ferrite, globular carbides	A15
145Cr6	spheroidization	207±7	Ferrite, globular cementite, elongated carbides	A16
x210Cr12 (D3)	spheroidization	229±4	Ferrite, globular and plate-like carbides	A17
S6-5-2 (M2)	spheroidization	233±9	Ferrite, carbide	A18

Table III

Detailed heat-treatments, hardness and microstructures of steels hardened and tempered at 550°C

Designation	Hardening	Hardness HV10	Microstructures	Fig.
Ck22 (1020)	820°C 15 min water	247±15	tempered martensite	A19
Ck35 (1035)		304±8		A20
C45 (1045)		295±3		A21
Ck53		320±1		A22
C60 (1060)		347±4		A23
28Cr4	840°C 15 min water	304±6	tempered martensite	A24
34Cr4 (5132)		318±7		A25
41Cr4 (5140)		337±6		A26
16CrMo4	900°C, 15 min, oil	322±5	Bainite	A27
25CrMo4	880°C, 15 min, oil	317±3	Bainite	A28
34CrMo4 (4137)	840°C, 15 min, warm bath	355±7	Tempered martensite	A29
42CrMo4 (4140)	840°C, 15 min, warm bath	381±10	Tempered martensite	A30
50CrMo4	840°C 15 min, warm bath	388±7	Tempered martensite	A31

Note: All these samples were tempered at 550°C for 60 min in a warm bath.

Table IV

Detailed heat-treatments, hardness and microstructures of steels hardened and tempered between 170°C and 200°C

Designation	Hardening	Tempering	Hardness HV10	Microstructures	Fig.
Ck22 (1020)	820°C 15 min water	180°C 60 min warm bath	503±10		A32
Ck35 (1035)			595±10		A33
C45 (1045)			627±7	Martensite, retained austenite	A34
Ck53			676±2		A35
C60 (1060)			711±11		A36
28Cr4	840°C 15 min warm bath	180°C 60 min warm bath	497±9		A37
34Cr4 (5132)			536±16	Martensite, retained austenite	A38
41Cr4 (5140)			620±9		A39
16CrMo4	900°C, 15 min, oil	180°C, 90 min, warm bath	474±1	Bainite, martensite	A40
25MrMo4	880°C, 15 min, oil	180°C, 90 min, warm bath	498±5	Bainite, martensite	A41
34CrMo4 (4137)	840°C, 15 min, warm bath	180°C, 60 min, warm bath	563±14	Martensite, retained austenite	A42
42CrMo4 (4140)	840°C, 15 min, warm bath	180°C, 60 min, warm bath	632±10		A43
50CrMo4	840°C, 15 min, warm bath	180°C, 60 min, warm bath	680±9		A44
90Cr3	800°C, 10 min, water	170°C, 60 min, warm bath	808±9	Martensite, carbide, retained austenite	A45
100V1 (W210)	820°C, 10 min, water	170°C, 60 min, warm bath	829±10	Martensite, carbide, retained austenite	A46
145Cr6	840°C, 10 min, warm bath	170°C, 60 min, warm bath	862±9	Martensite, carbide, carbides at grain boundaries, retained austenite	A47
x210Cr12 (D3)	940°C, 20 min, oil	200°C, 90 min, warm bath	787±10	Martensite, plate-like carbides, retained austenite	A48

Table V

Weight losses with SiC papers from two different batches

"As-received" steels	Weight losses (mg)	
	Batch I	Batch II
C15	435,1±50,9	310,9±35,5
100V1	537,1±21,2	413,3±42,0
x210Cr12	190,6± 7,4	158,8± 3,8
S6-5-2	309,9±59,4	238,9± 3,0
C60	272,3±36,3	220,9±13,7
41Cr4	200,1±19,4	192,3± 7,7
50CrMo4	298,5±18,8	245,1±23,7

Table VI

Wear resistance values of carbon steels abraded by flint

Steels	Normalized		Hardened and tempered at 550°C		Hardened and tempered at 180°C	
	HV10	Wear resistance values [g^{-1}]	HV10	Wear resistance values [g^{-1}]	HV10	Wear resistance values [g^{-1}]
C15	137±1	13,81±0,71				
Ck22	161±1	17,60±1,53	247±15	10,90±1,73	503±10	51,44±4,87
Ck35	179±3	16,85±1,39	304±8	19,30±3,45	595±10	103,17±7,04
C45	202±7	23,19±3,85	295±3	25,29±2,13	627±7	129,65±26,40
Ck53	225±6	31,59±5,23	320±1	25,38±5,77	676,±2	183,83±23,06
C60	242±4	28,39±5,60	347±4	25,28±5,36	711±11	209,92±106,41

Table VII

Wear resistance values of carbon steels abraded by silicon carbide

Steels	Normalized		Hardened and tempered at 550°C		Hardened and tempered at 180°C	
	HV10	Wear resistance values [g^{-1}]	HV10	Wear resistance values [g^{-1}]	HV10	Wear resistance values [g^{-1}]
C15	137±1	2,40±0,29				
Ck22	161±1	2,36±0,11	247±15	3,06±0,71	503±10	13,46±0,32
Ck35	179±3	2,67±0,19	304±8	3,27±0,26	595±10	20,95±1,63
C45	202±7	3,02±0,23	295±3	3,22±0,15	627±7	27,51±0,78
Ck53	225±6	3,27±0,18	320±1	2,84±0,21	676±2	32,08±1,56
C60	242±4	3,66±0,38	347±4	3,53±0,55	711±11	33,65±1,32

Table VIII

Wear resistance values of alloy steels abraded by flint

Alloys	"As-received"		Hardened and tempered at 550°C		Hardened and tempered at 180°C	
	HV10	Wear resistance values [g^{-1}]	HV10	Wear resistance values [g^{-1}]	HV10	Wear resistance values [g^{-1}]
28Cr4	189±1	27,1±4,2	304±6	38,5±4,4	497±9	313±62
34Cr4	208±3	23,1±2,0	318±7	30,7±2,1	536±16	284±25
41Cr4	251±1	25,9±4,3	337±6	22,4±2,3	620±9	211±40
16CrMo4			322±5	15,0±2,0	474±1	35,1±4,3
25CrMo4			317±3	16,3±1,1	498±5	33,1±3,4
34CrMo4	280±6	17,7±2,0	355±7	25,2±5,4	563±14	311±29
42CrMo4	311±10	25,9±1,9	381±10	33,8±5,1	632±10	333±60
50CrMo4	316±4	24,6±7,0	388±7	48,8±6,2	680±9	239±102
15Cr3	150±3	19,8±2,0				
90Cr3	171±4	28,8±4,2			808±9	127±9
145Cr6	207±7	52,0±10,6			862±9	345(1 test)
100V1	189	26,7±5,7				
x210Cr12	229±4	331±51				
S6-5-2	233±9	179±12				

Table IX

Wear resistance values of alloy steels abraded by silicon carbide

Alloys	"As-received"		Hardened and tempered at 550°C		Hardened and tempered at 180°C	
	HV10	Wear resistance values $[g^{-1}]$	HV10	Wear resistance values $[g^{-1}]$	HV10	Wear resistance values $[g^{-1}]$
28Cr4	189±1	2,69±0,20	304±6	6,32±0,12	497±9	22.6±1,4
34Cr4	208±3	3,17±0,15	318±7	5,74±0,22	536±16	21,2±1,3
41Cr4	251±1	4,70±0,49	337±6	4,13±0,09	620±9	22,1±1,3
16CrMo4			322±5	2,01±0,18	474±1	10,2±0,6
25CrMo4			317±3	2,76±0,14	498±5	10,4±1,0
34CrMo4	280±6	2,40±0,22	355±7	3,73±0,71	563±14	18,5±0,9
42CrMo4	311±10	4,23±0,54	381±10	4,82±0,37	632±10	17,8±1,1
50CrMo4	316±4	3,32±0,28	388±7	5,76±0,42	680±9	19,2±1,5
15Cr3	150±3	2,62±0,34				
90Cr3	171±4	2,20±0,07			808±9	17,1±1,5
145Cr6	207±7	2,32±0,07			862±9	13,3±1,4
100V1	189	1,85±0,13			829±10	15,1±1,0
x210Cr12	229±4	5,37±0,23			787±10	11,6±0,3
S6-5-2	233±9	3,12±0,39				

Table X

Results of the calculation of regression equations for carbon steels

Heat treatment	Dependent variable, x	Flint	SiC
Normalized	HV10	m = 0,1660 b = -9,80 corr.: 0,94	m = 0,0153 * b = -0,094 corr.: 0,99
	w% C	m = 38,83 b = 6,59 corr.: 0,92	m = 3,02 b = 1,71 corr.: 0,98
Hardened and tempered at 550°C	HV10	m = 0,1461 b = -22,99 corr.: 0,85	m = 0,0047** b = 1,875 corr.: 0,98
	w% C	m = 37,92 b = 4,81 corr.: 0,92	m = 1,1484** b = 2,806 corr.: 0,95
Hardened and tempered at 180°C	HV10	m = 0,7798 b = -349,7 corr.: 0,99	m = 0,1028 b = -38,43 corr.: 0,99
	w% C	m = 409,9 b = -41,88 corr.: 0,99	m = 54,0 b = 2,15 corr.: 0,99

Regression equation: $W^{-1} = mx + b$

* The results obtained with the steel C15 were not included in the calculations.

** The results obtained with the steel Ck53 were not included in the calculations.

Table XI

Relative wear resistance of alloy steels

Alloys	Cr/C atomic ratio	Abrasion by flint			Abrasion by SiC		
		As-received	Tempered at 550°C	Tempered at 180°C	As-received	Tempered at 550°C	Tempered at 180°C
28Cr4	0,80	1,25	1,80	8,29	0,96	1,91	1,79
34Cr4	0,73	0,94	1,31	4,16	1,03	1,70	1,27
41Cr4	0,54	0,81	0,85	1,58	1,25	1,19	0,87
16CrMo4	1,26		0,62	1,76		0,59	0,99
25CrMo4	0,93		0,70	0,86		0,82	0,81
34CrMo4	0,72	0,48	0,87	3,49	0,57	1,05	0,95
42CrMo4	0,59	0,62	1,03	2,33	0,91	1,32	0,67
50CrMo4	0,42	0,58	1,45	1,33	0,70	1,56	0,61
15Cr3	0,94	1,31			1,19		
90Cr3	0,20	1,55		0,45	0,87		0,38
145Cr6	0,23	2,12		1,07	0,75		0,26
100V1		1,24			0,66		0,32
x210Cr12	1,34	11,7			1,57		0,27
S6-5-2		6,20			0,90		

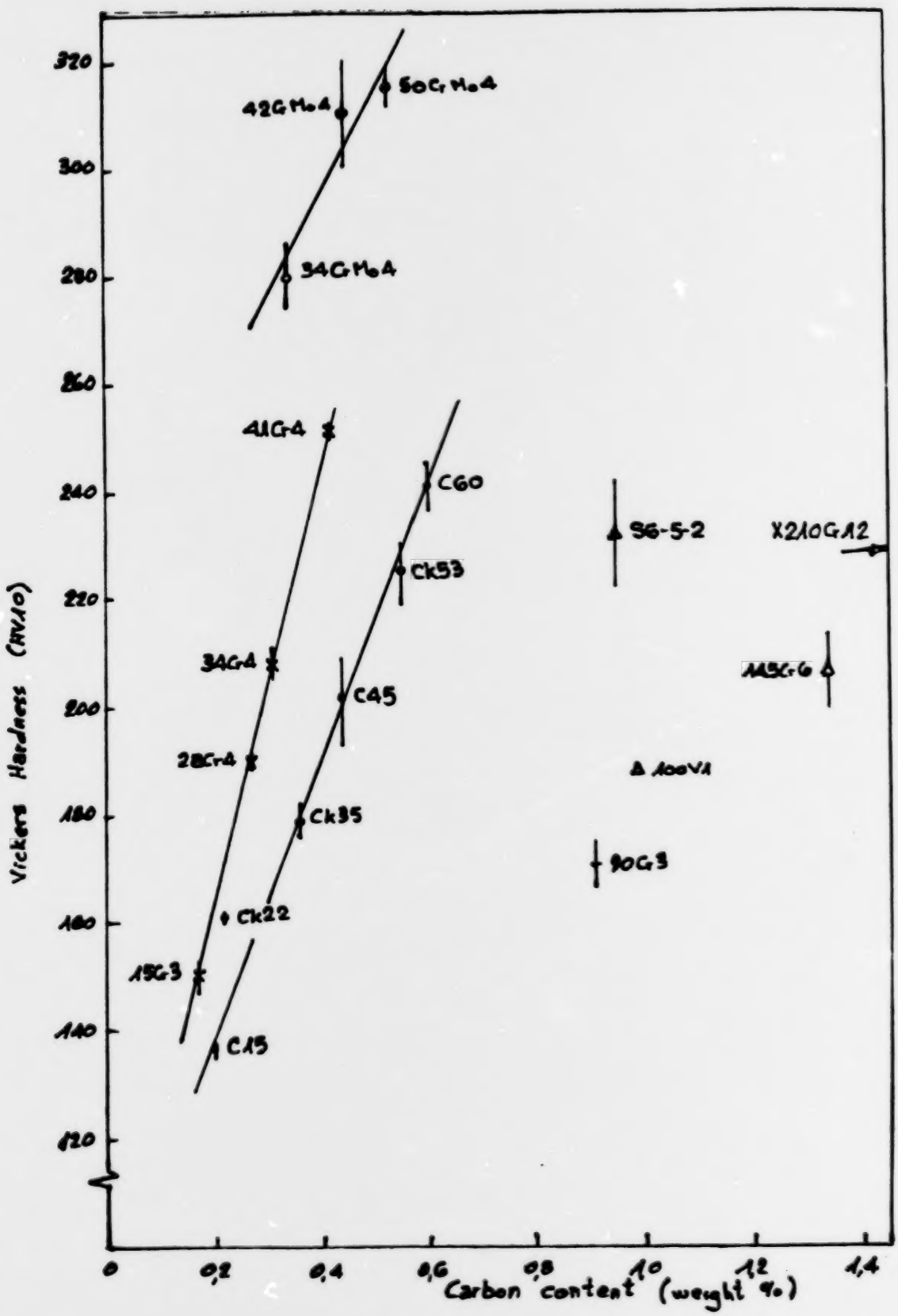


Fig. 1 Relation between hardness and carbon content of the steels in the "as-received" condition.

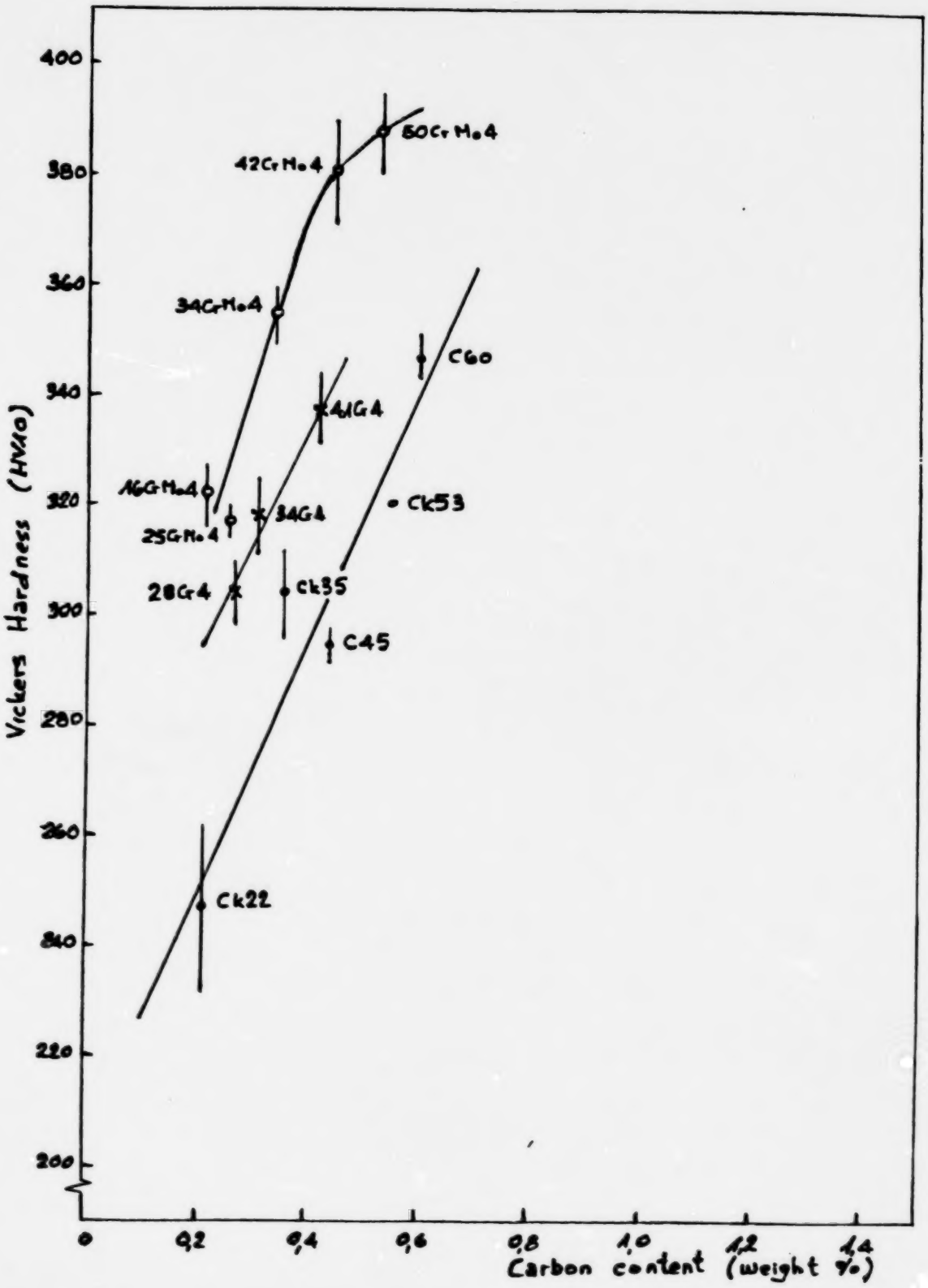


Fig. 2 Relation between hardness and carbon content of the steels hardened and tempered at 550°C.

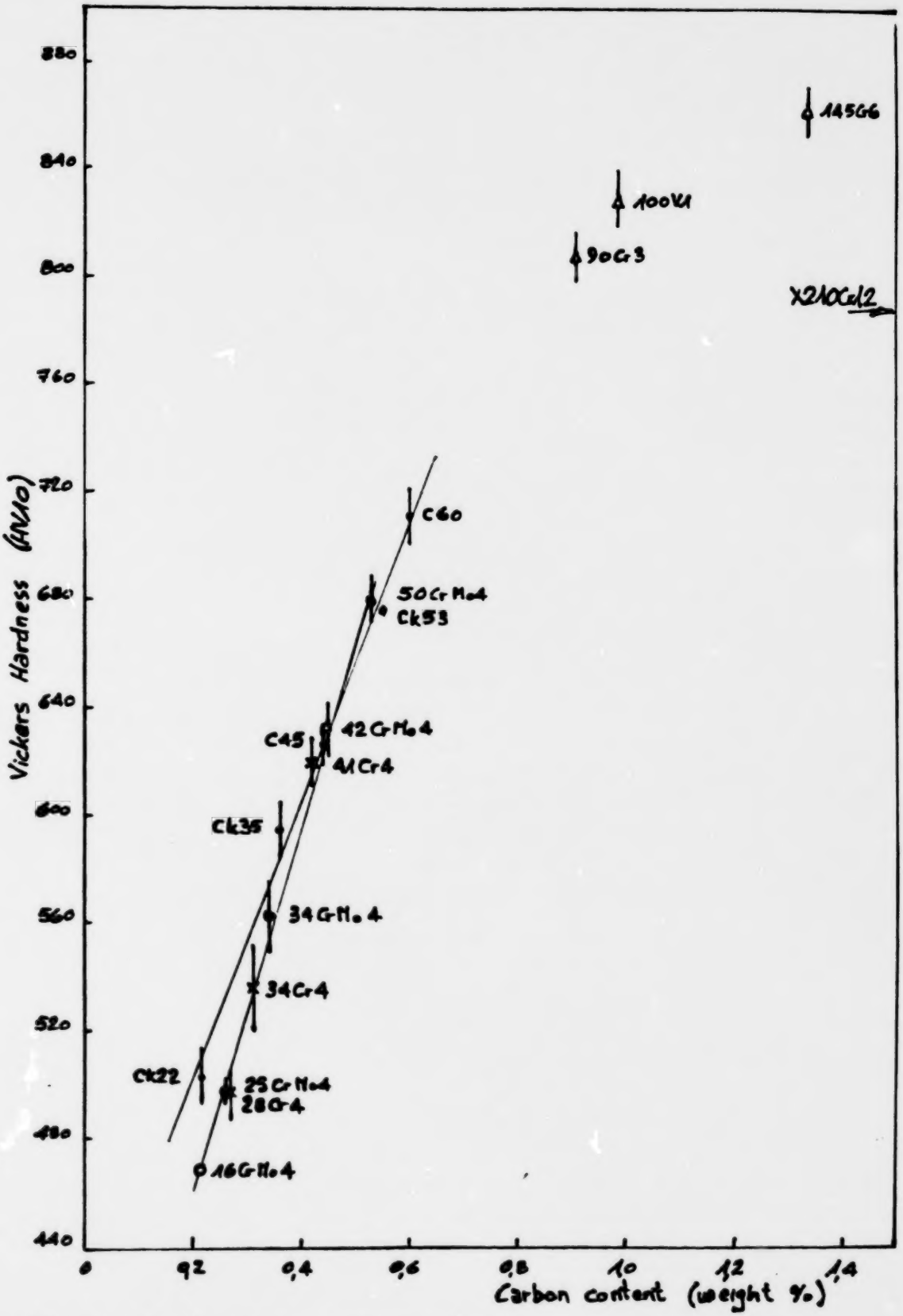


Fig. 3 Relation between hardness and carbon content of the steels hardened and tempered between 170°C and 200°C.

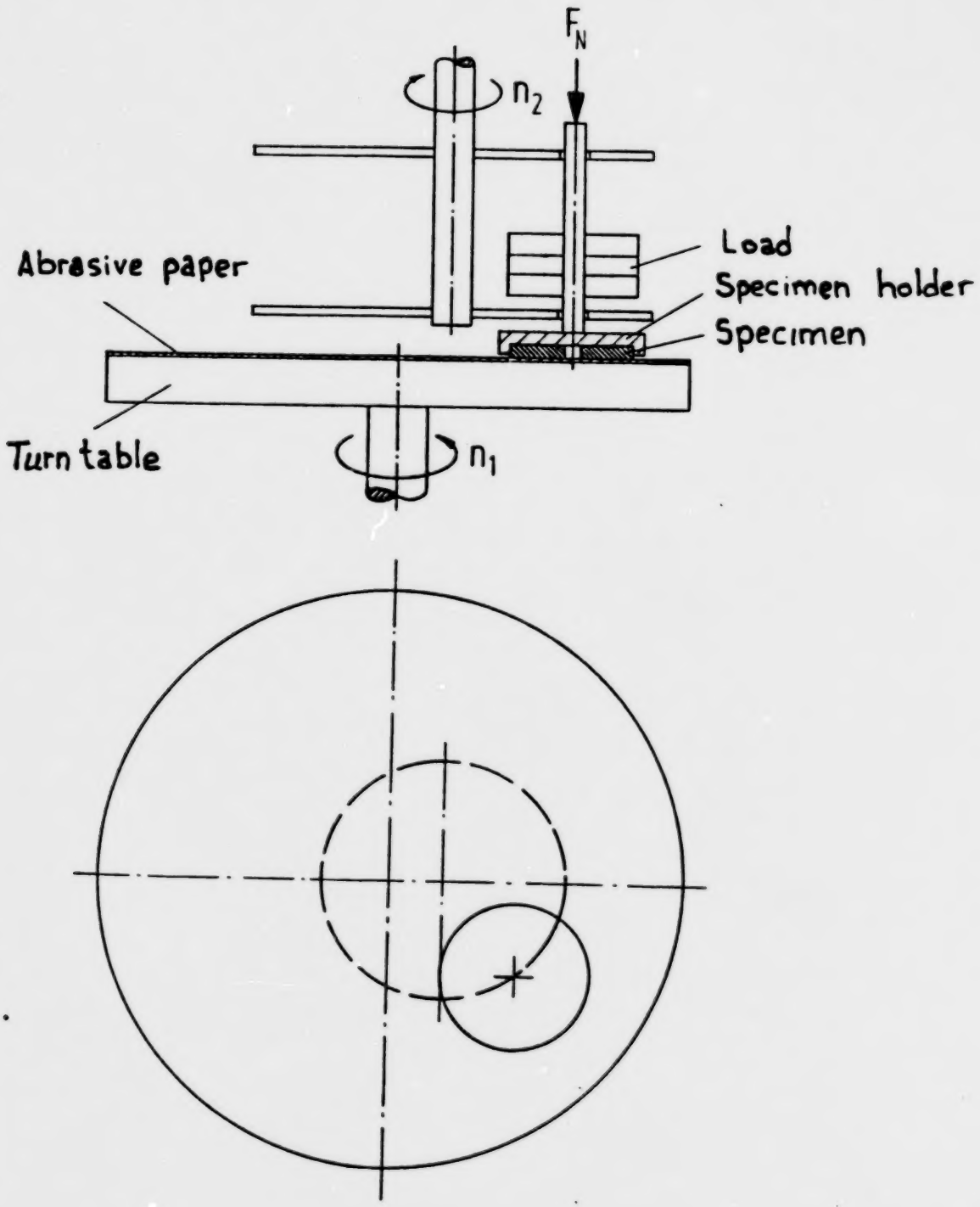


Fig. 4 Schematic of the wear test rig.

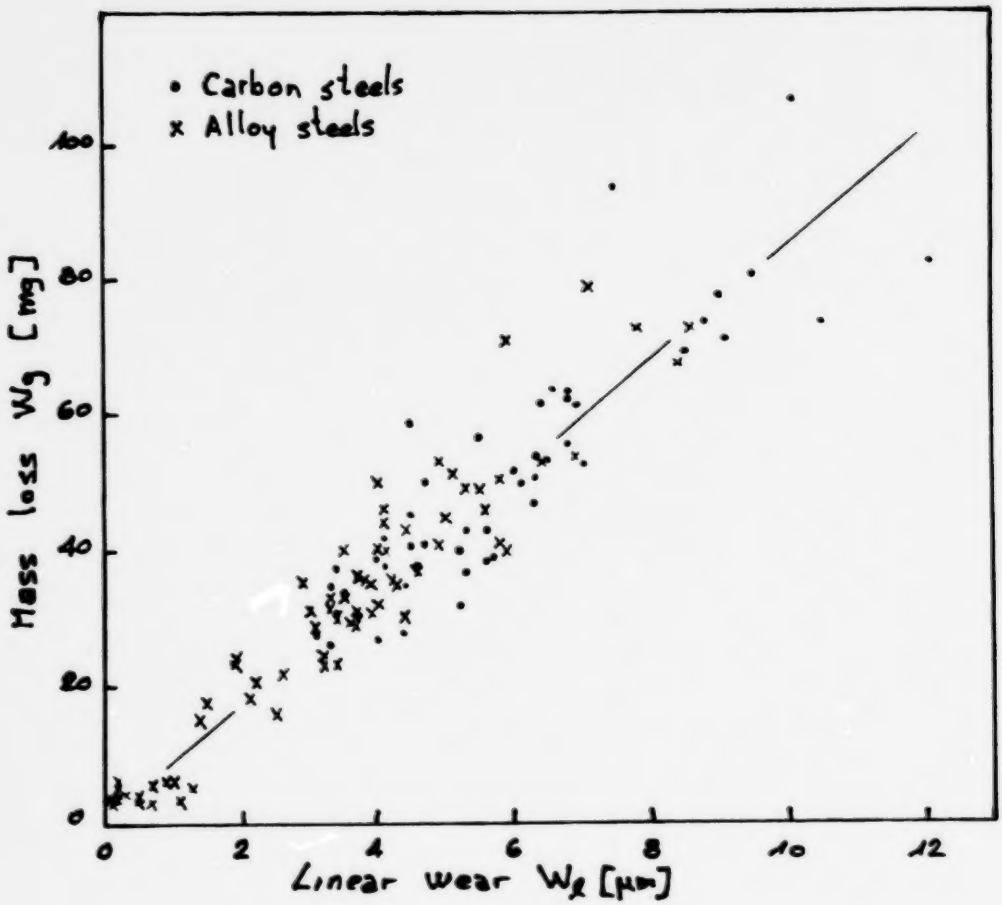


Fig. 5 Relation between the thickness change and the weight loss of steels abraded by flint.

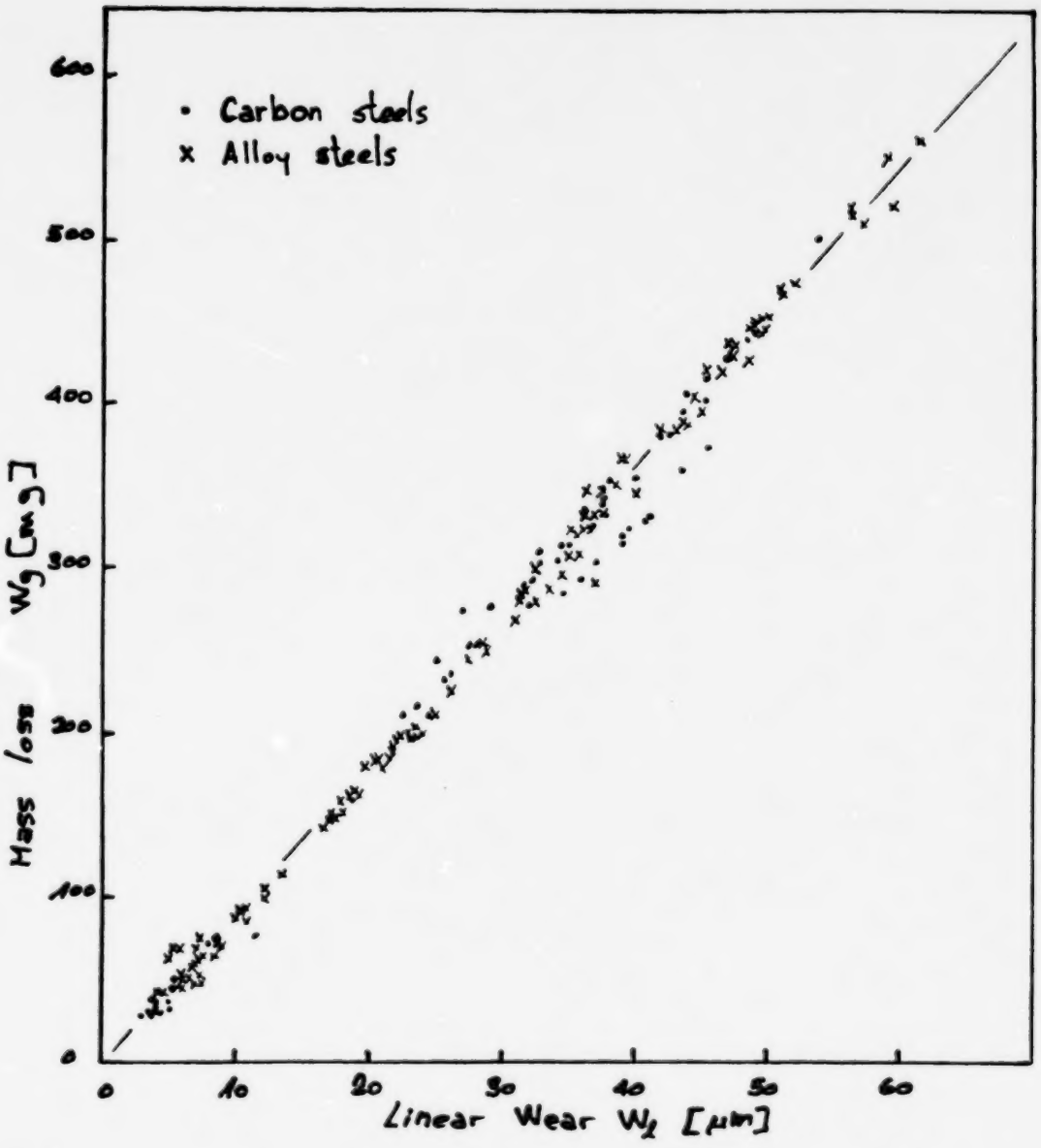


Fig. 6 Relation between the thickness change and the weight loss of steels abraded by silicon carbide

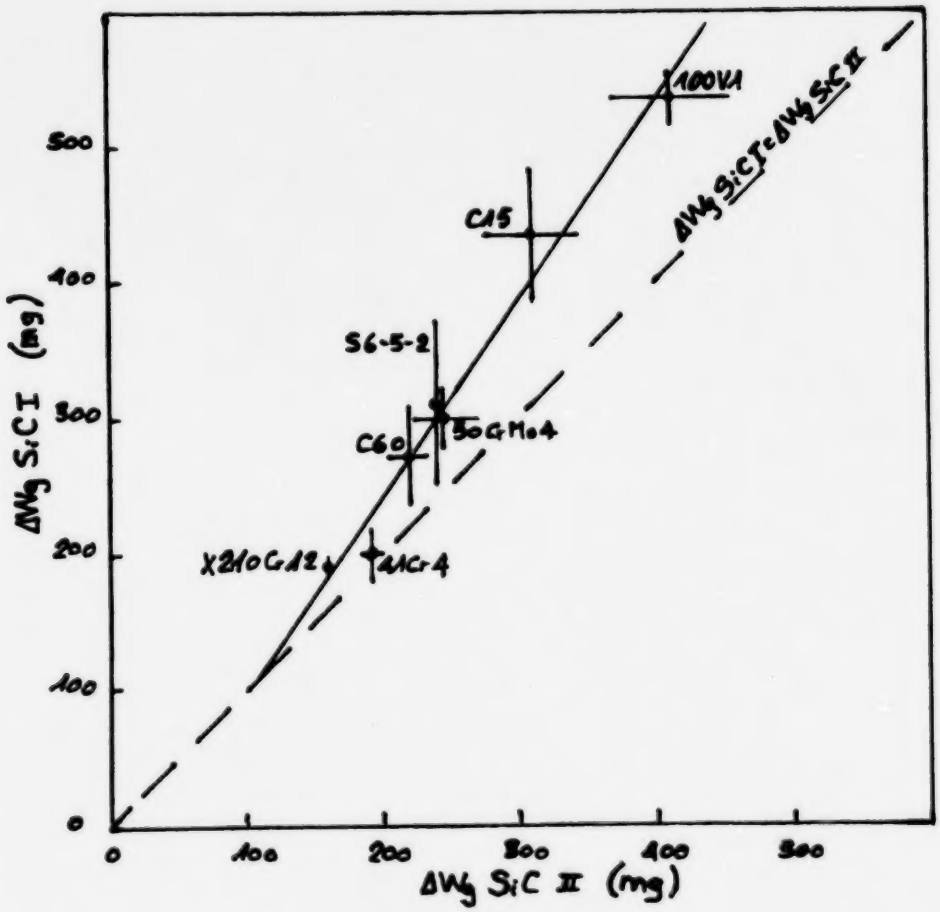


Fig. 7 Comparison between the weight loss produced by two different batches of silicon carbide abrasive papers of the same nominal denomination (220 grit).

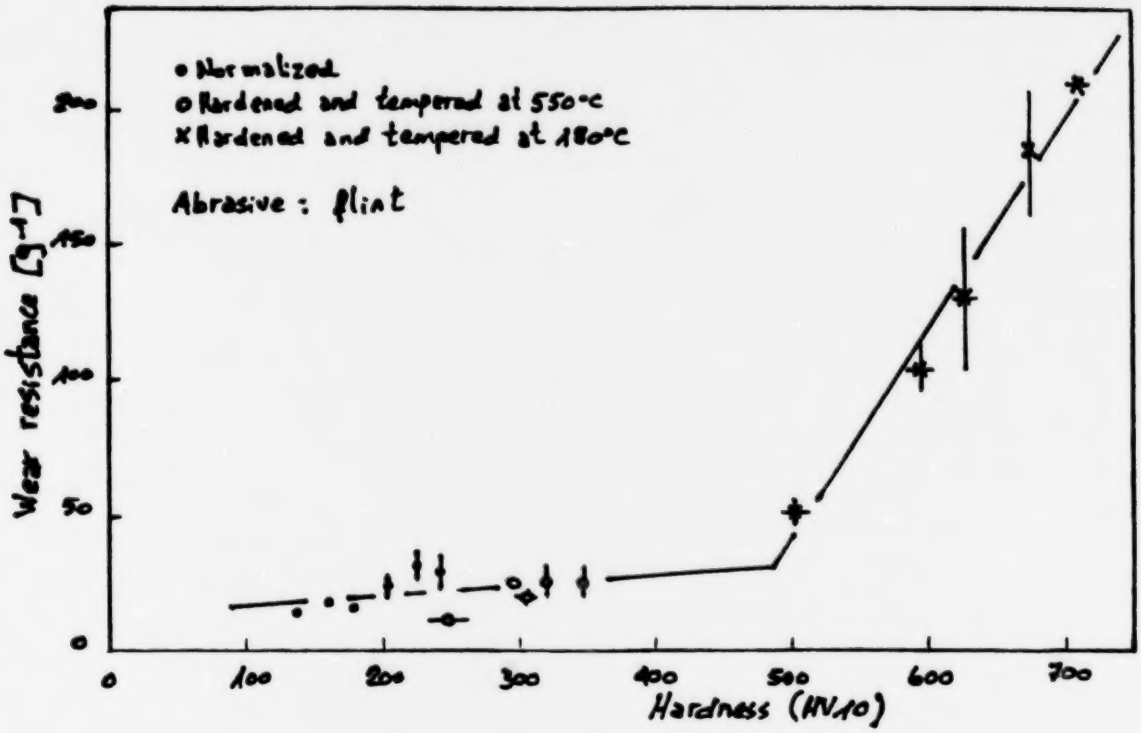


Fig. 8 Relation between wear resistance and hardness of carbon steels abraded by flint.

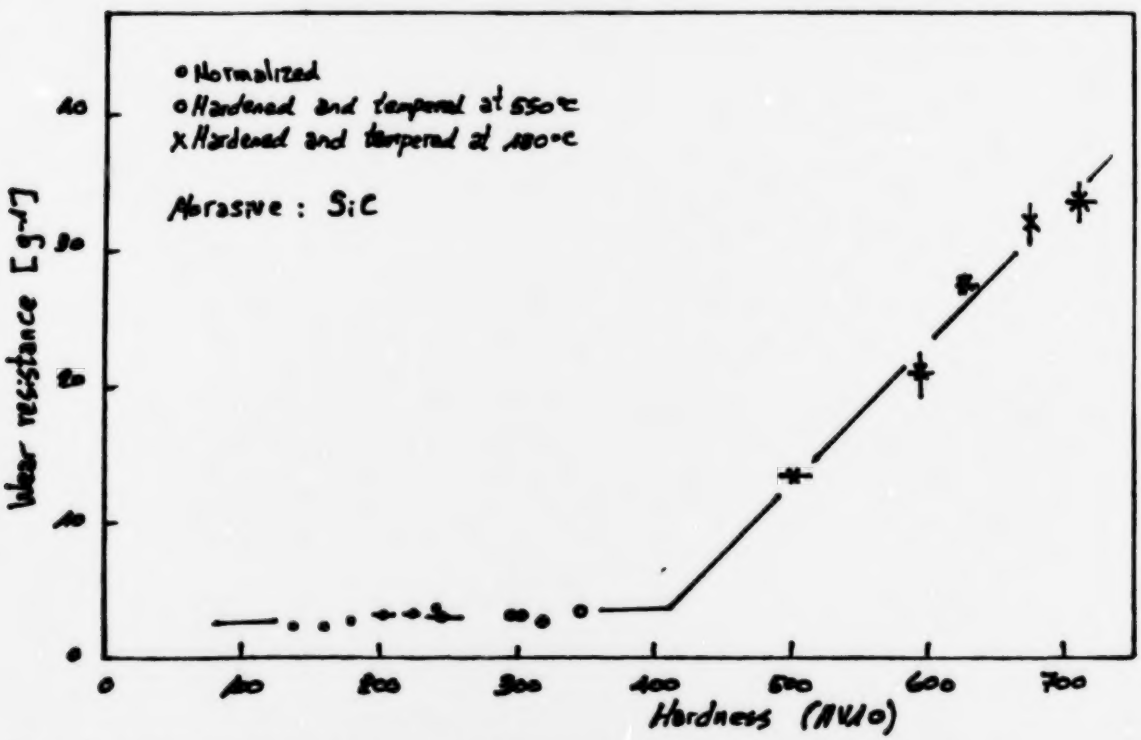


Fig. 9 Relation between wear resistance and hardness of carbon steels abraded by silicon carbide.

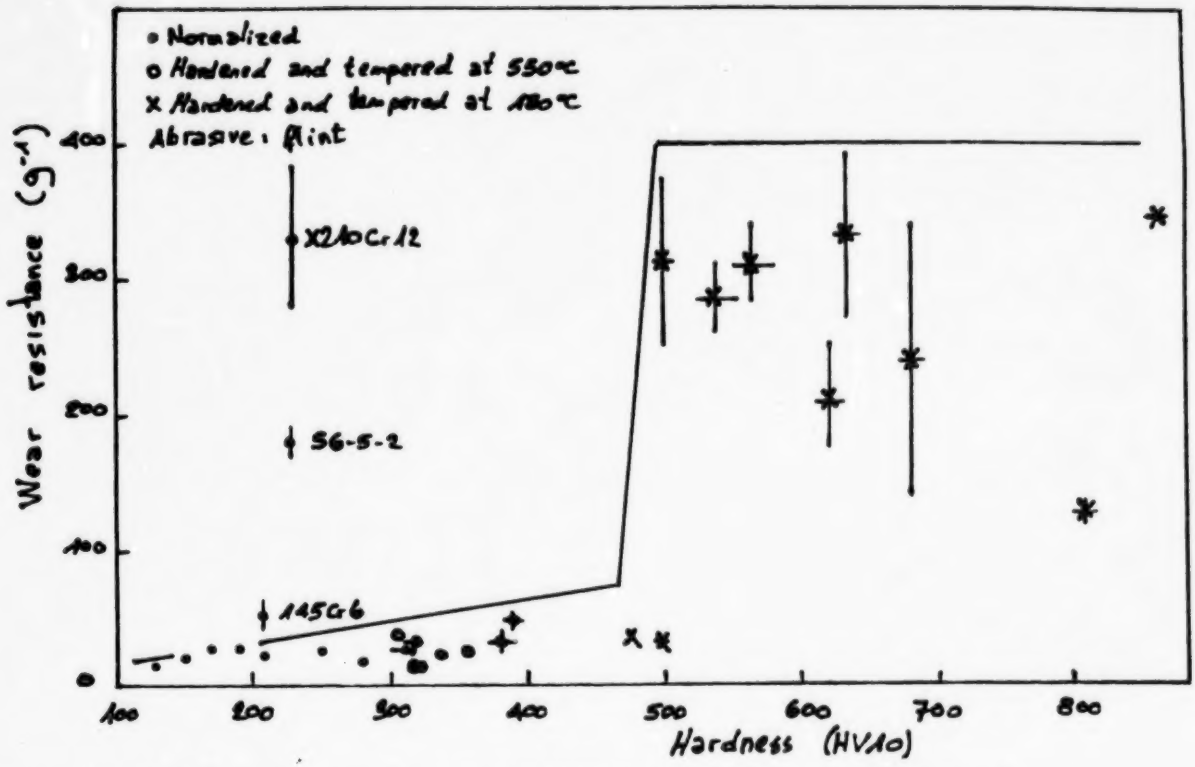


Fig. 10 Relation between wear resistance and hardness of alloy steels abraded by flint.

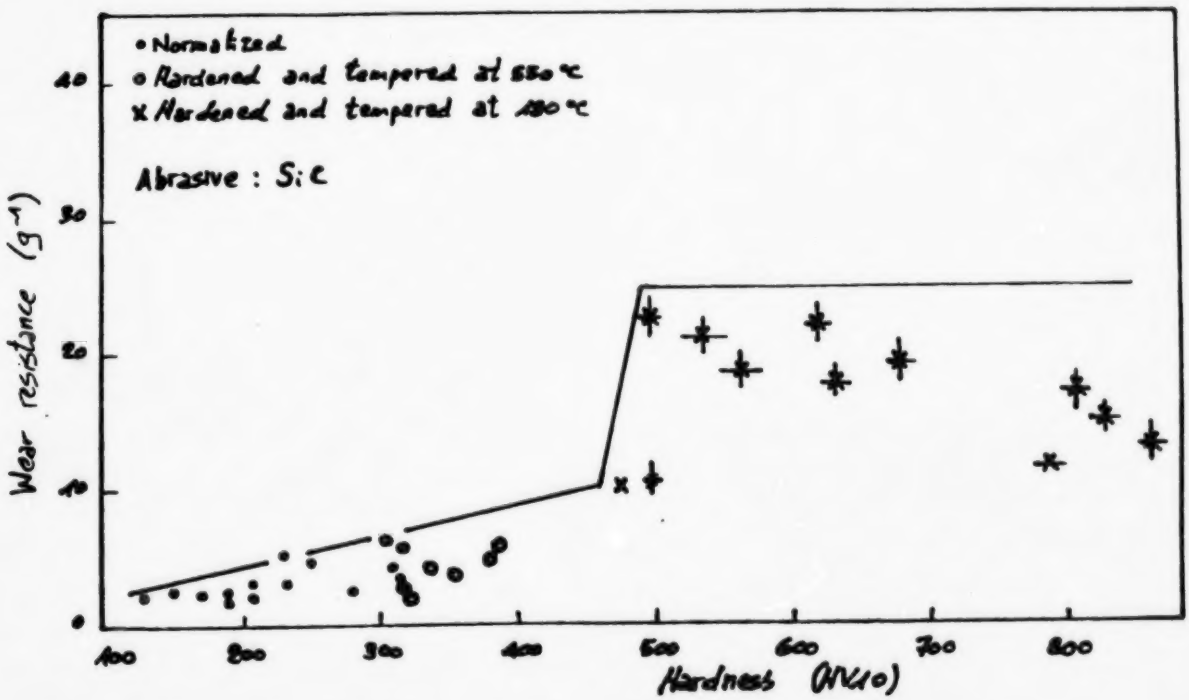


Fig. 11 Relation between wear resistance and hardness of alloy steels abraded by silicon carbide.

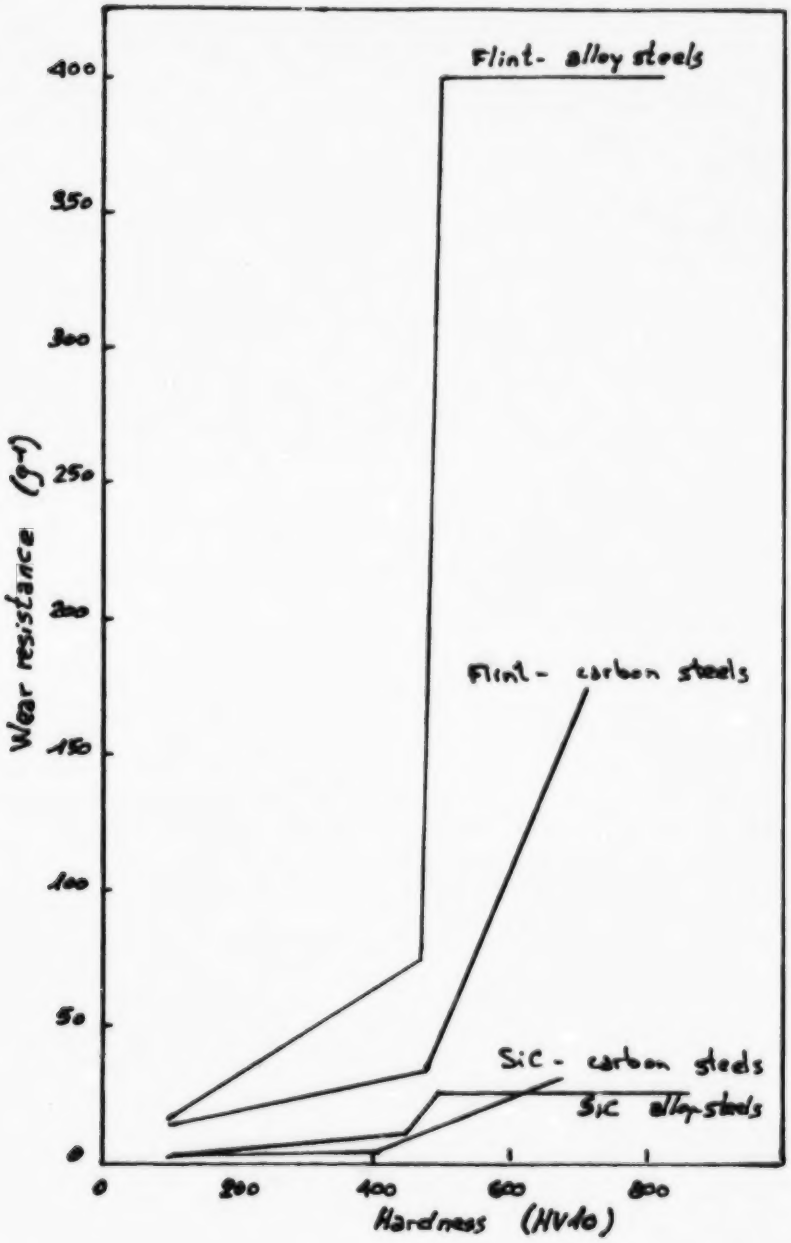
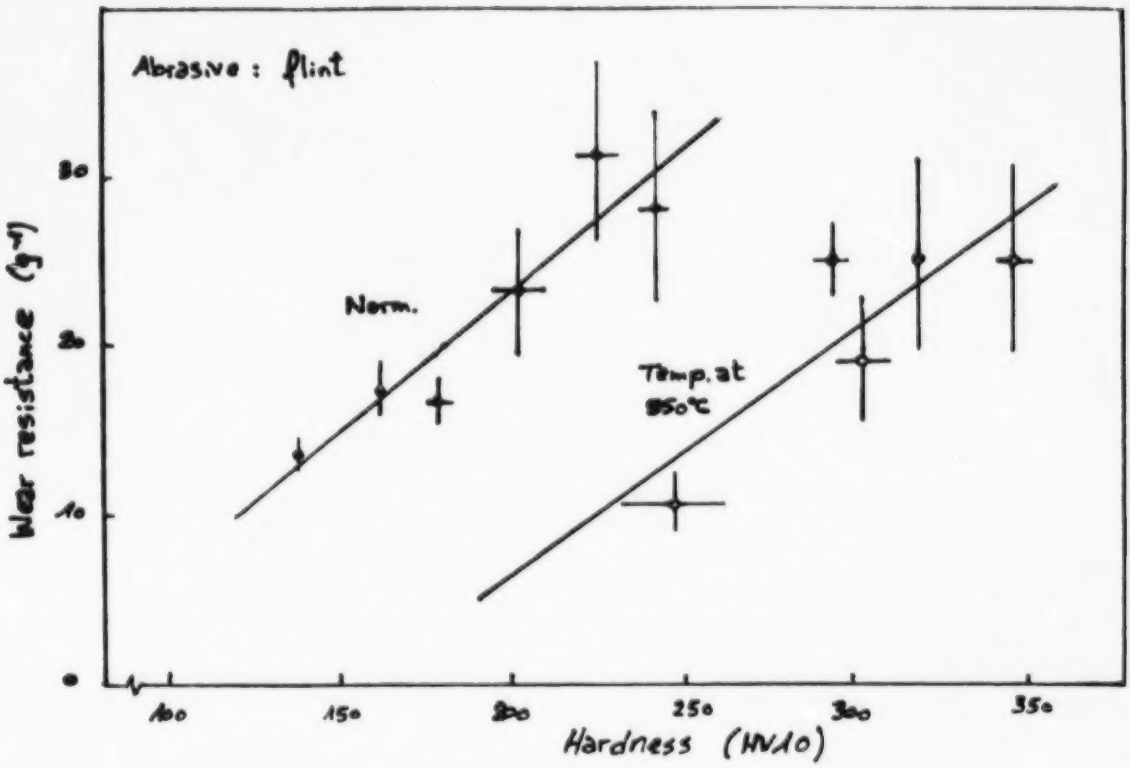


Fig. 12 Schematic relation between wear resistance and hardness of carbon steels and alloy steels abraded by flint and silicon carbide.



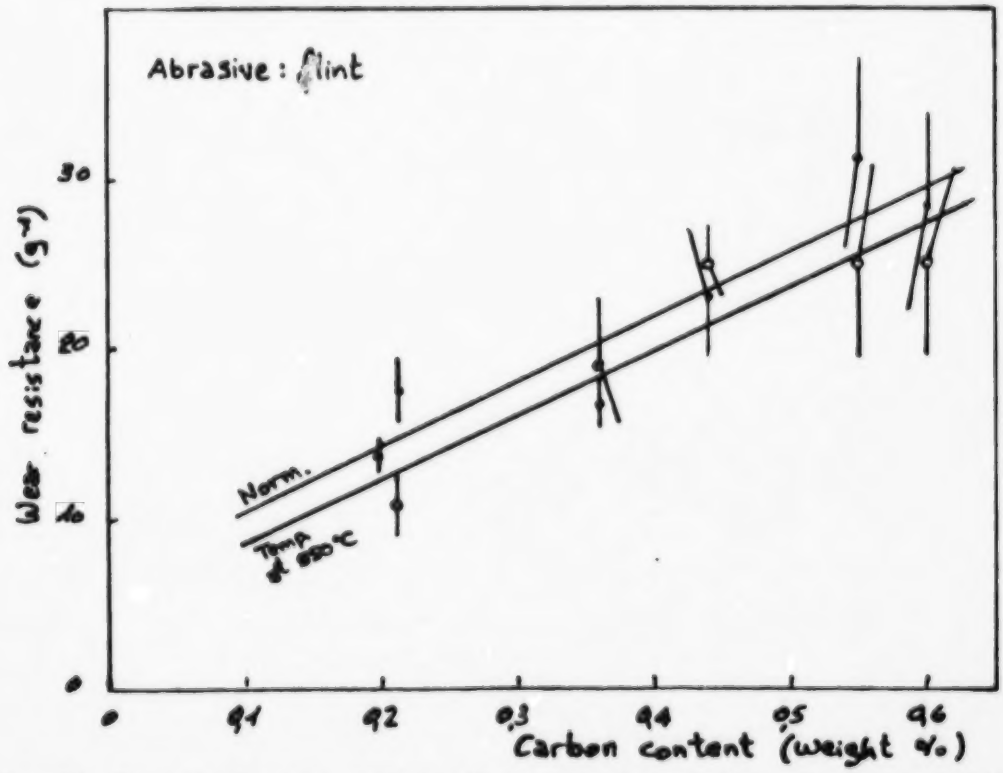
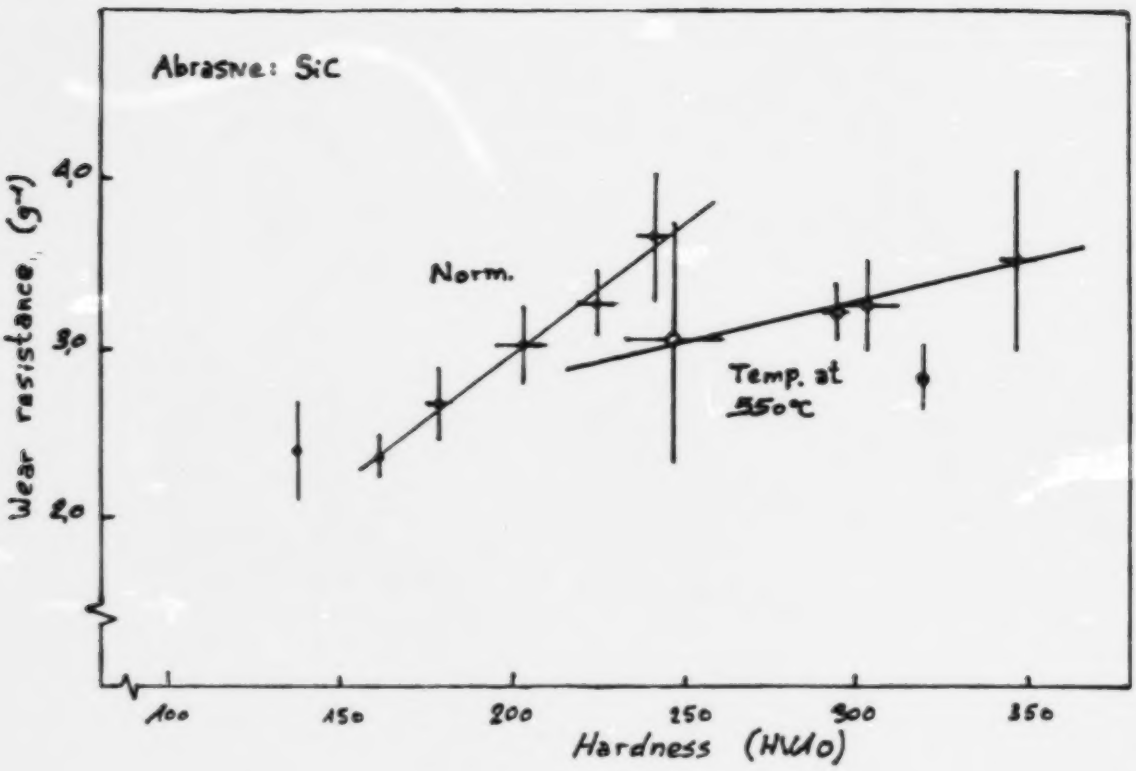


Fig. 13 Wear resistance against flint of plain carbon steels normalized (•) and hardened and tempered at 550°C (o) plotted a) versus the bulk hardness values, b) versus the carbon content.



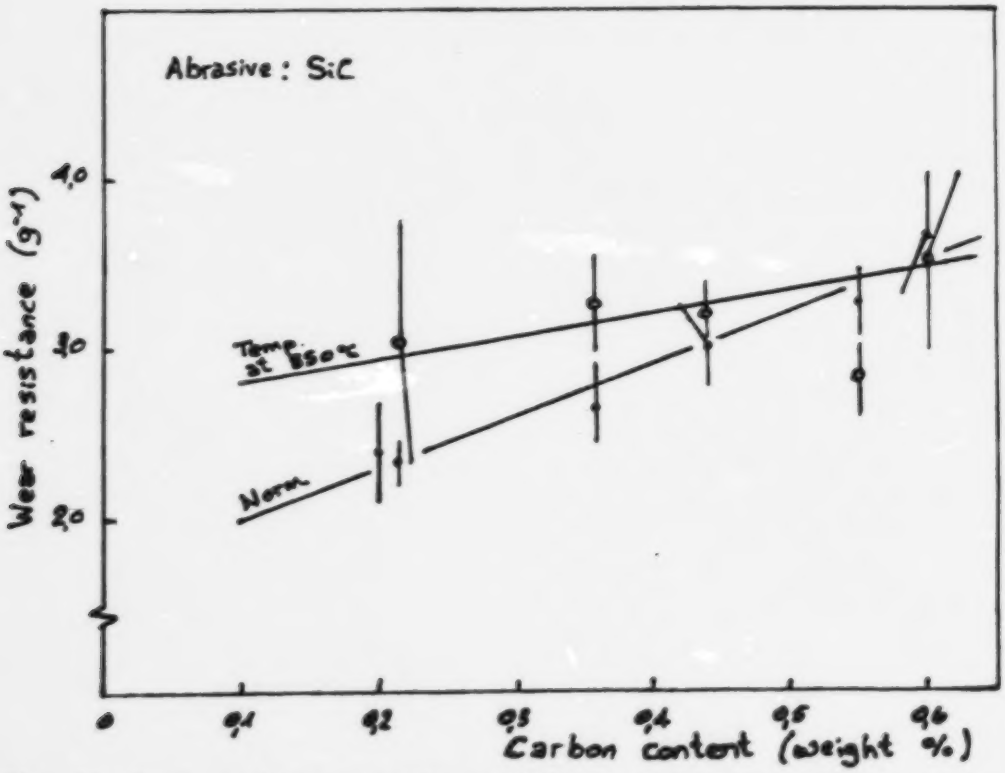


Fig. 14 Wear resistance against silicon carbide of plain carbon steels normalized (•) and hardened and tempered at 550°C (o) plotted

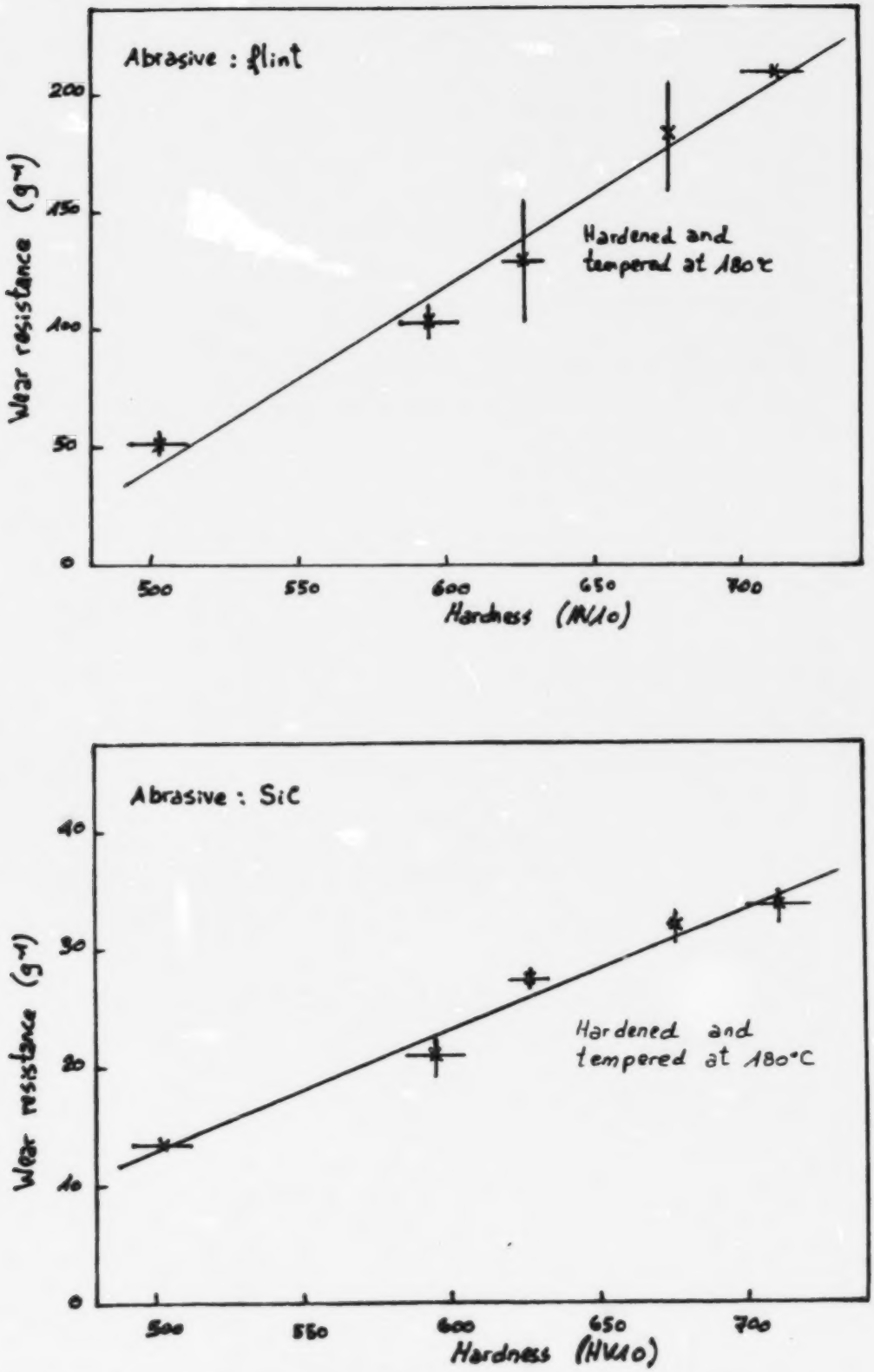
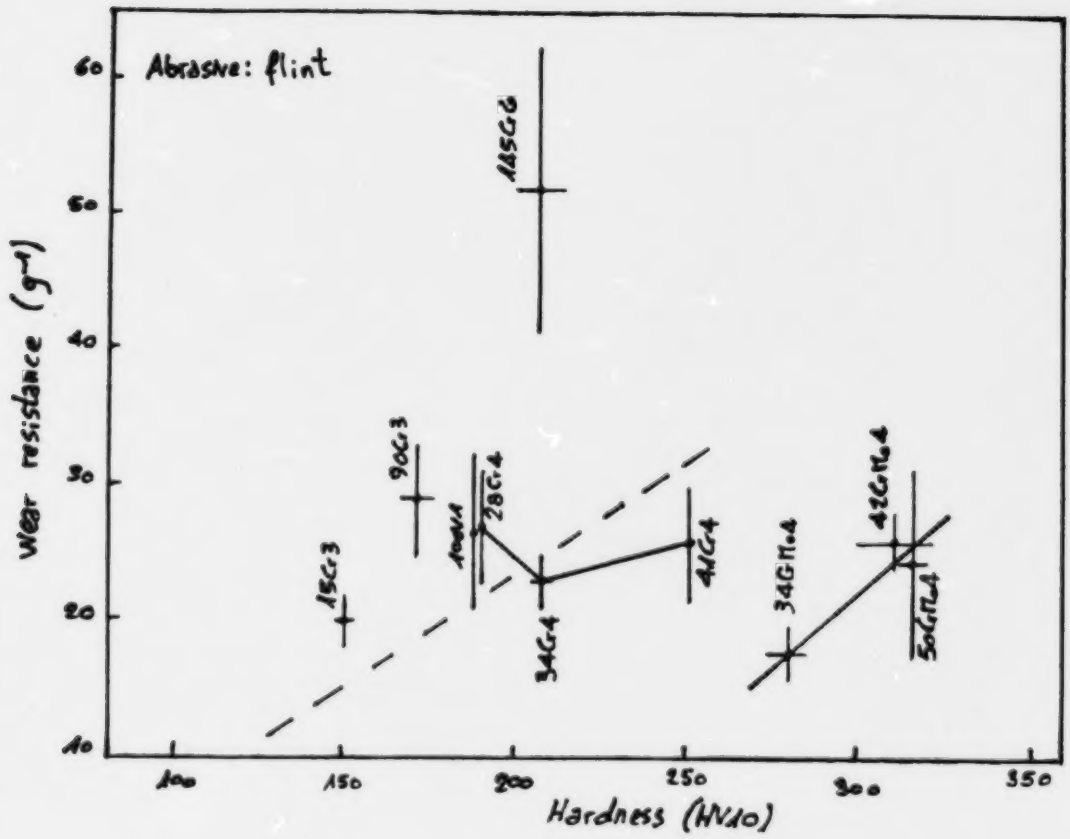


Fig. 15 Wear resistance of carbon steels hardened and tempered at 180°C plotted versus the bulk hardness values a) flint, b) SiC.



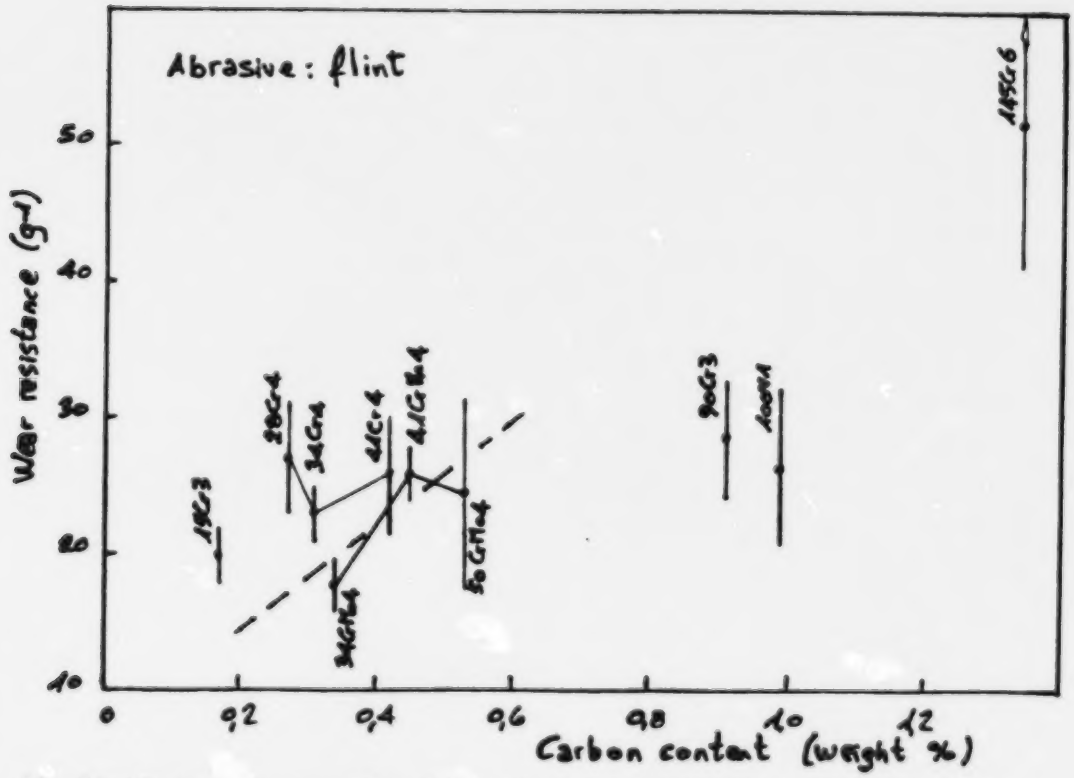


Fig. 16 Resistance to wear by flint of the normalized alloy steels plotted against a) the bulk hardness, b) the carbon content

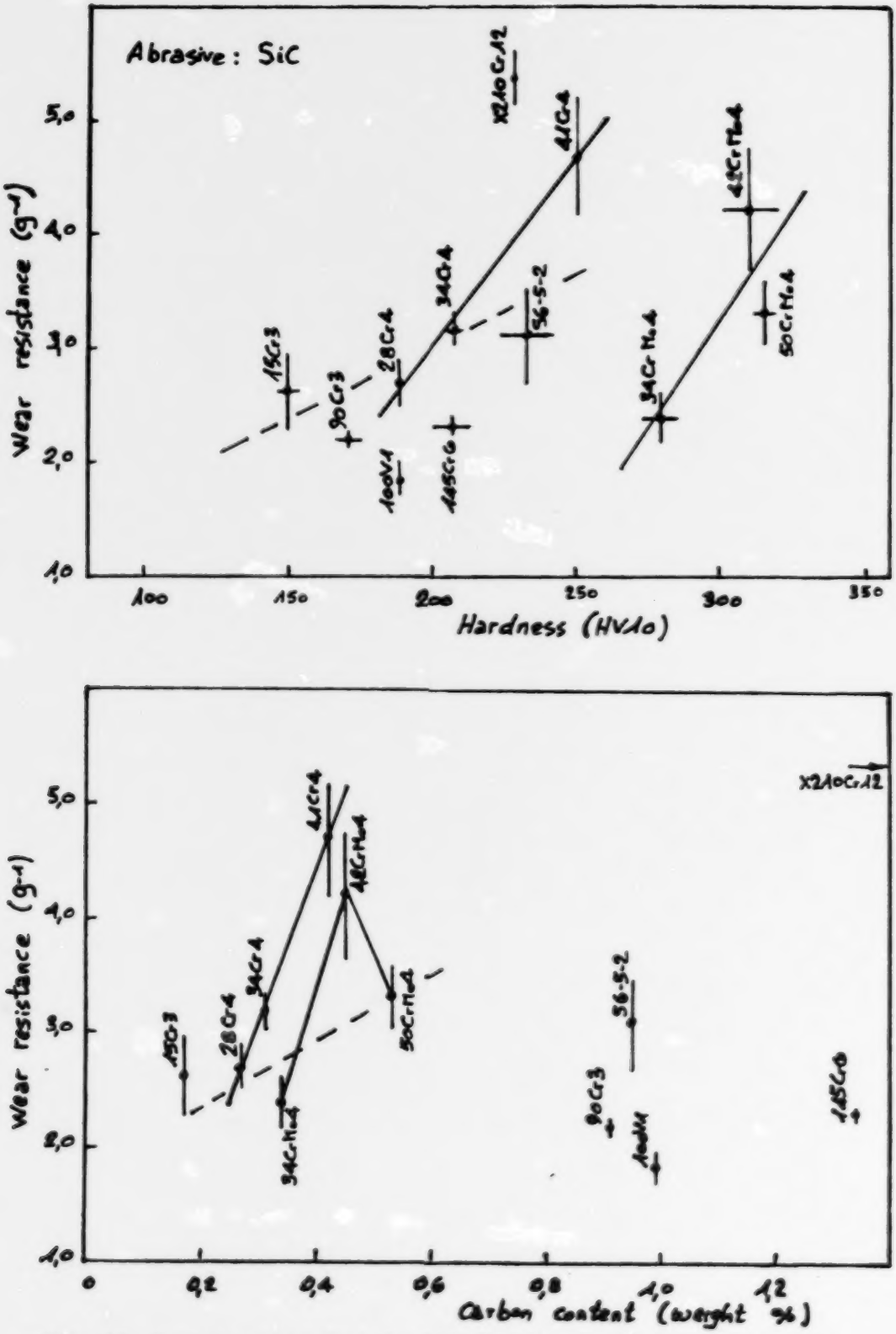
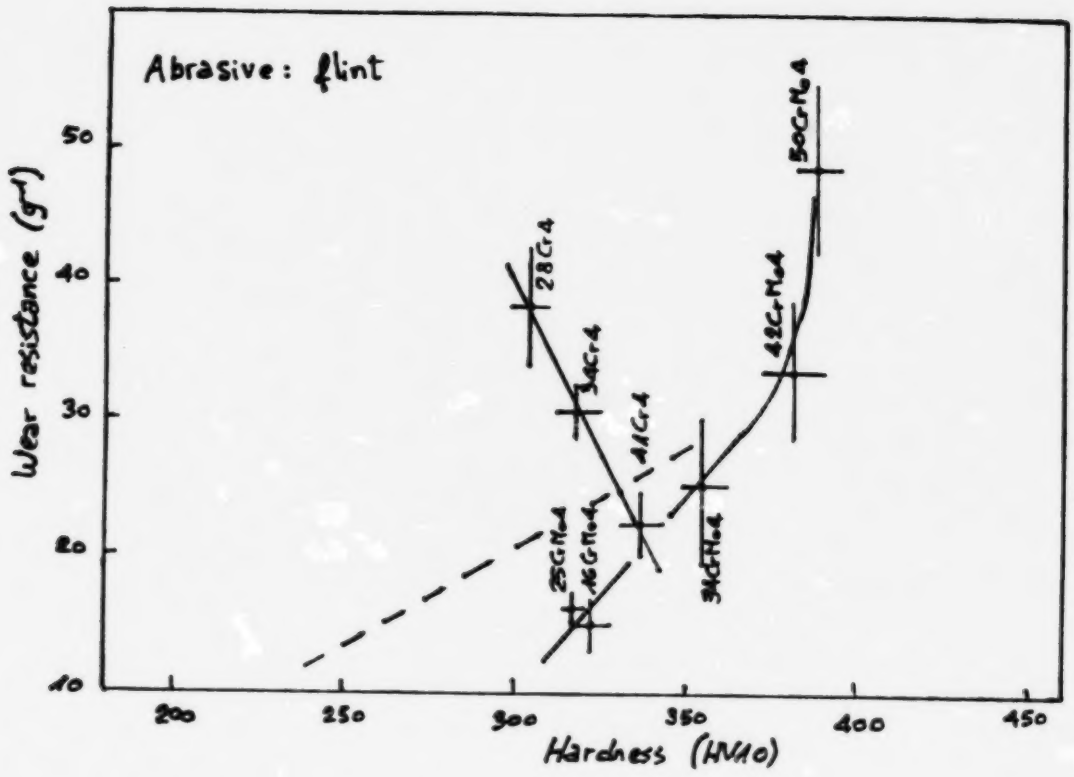


Fig. 17 Resistance to wear by SiC of the normalized alloy steels plotted against a) the bulk hardness, b) the carbon



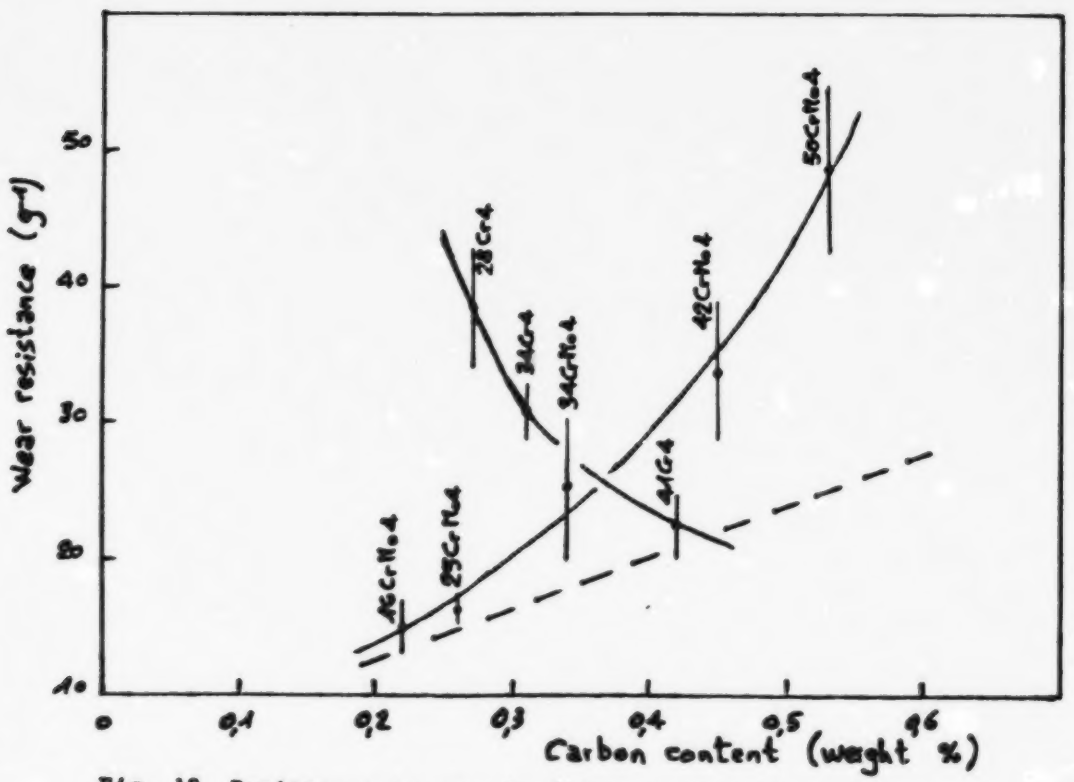
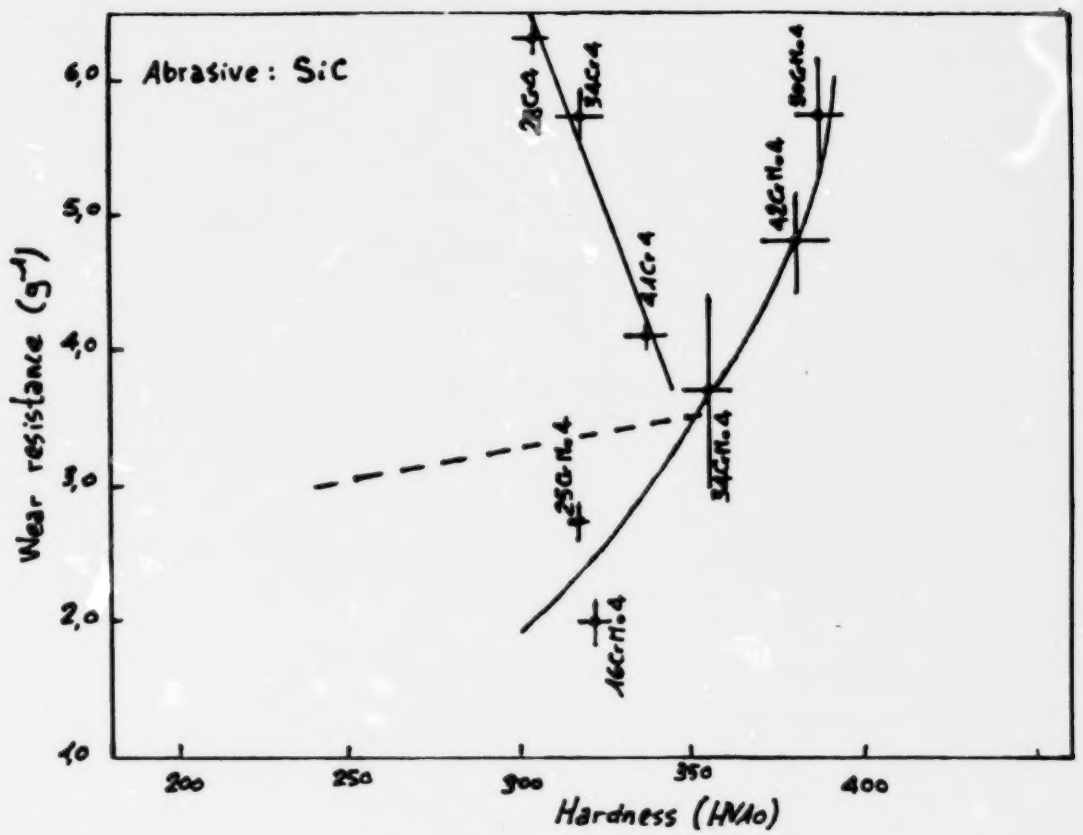


Fig. 18 Resistance to wear by flint of the alloys steels hardened and tempered at 550°C plotted against a) the bulk hardness, b) the carbon content.



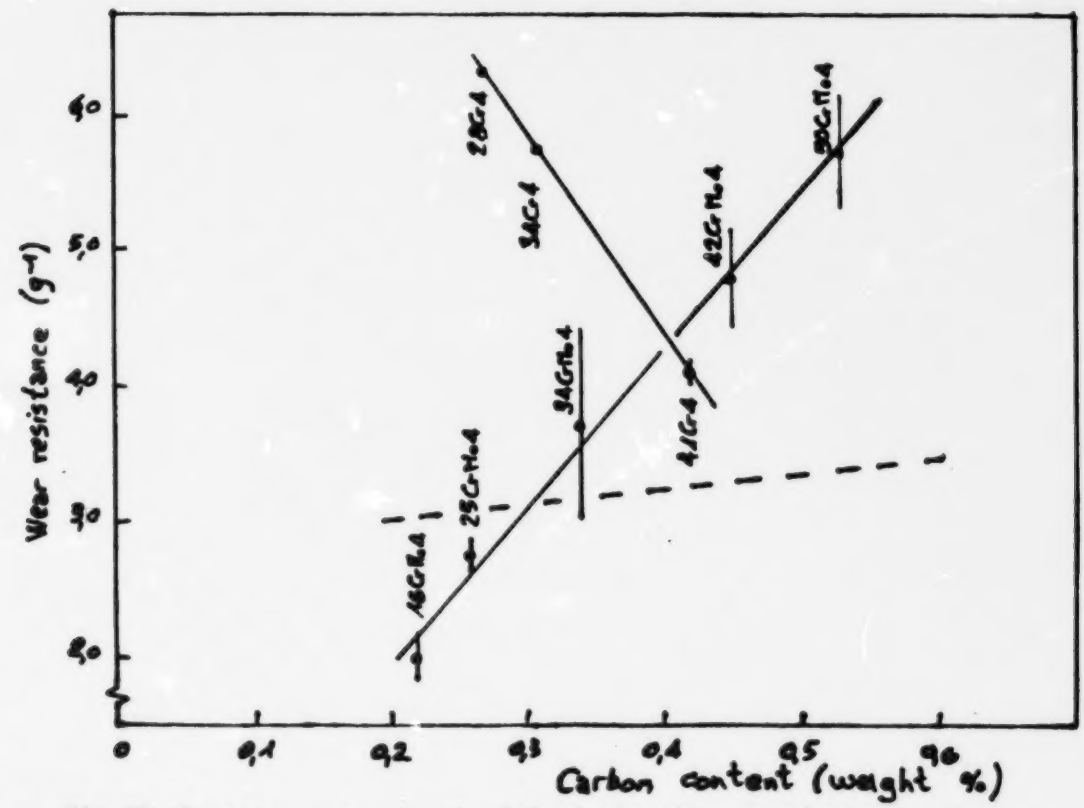


Fig.19 Resistance to wear by SiC of the alloy steels hardened and tempered at 550°C plotted against a) the bulk

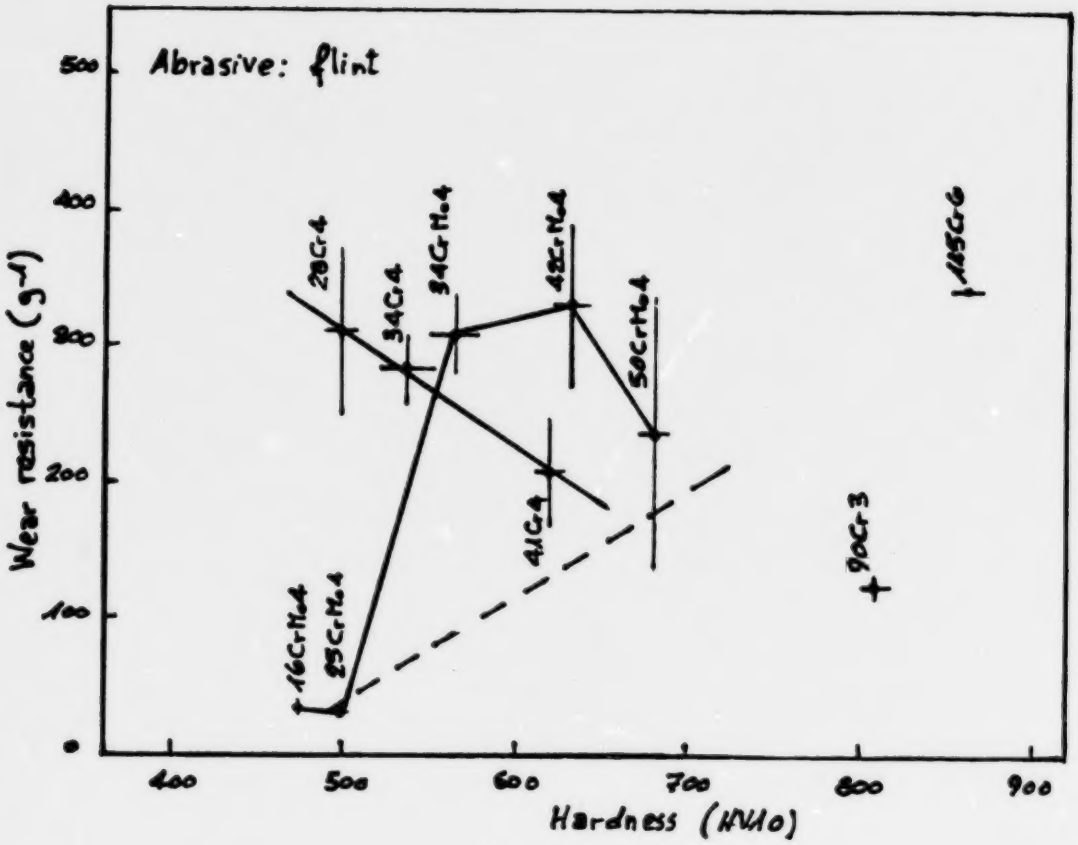


Fig. 20 Resistance to wear by flint of the alloy steels hardened and tempered at 180°C plotted against the bulk hardness.

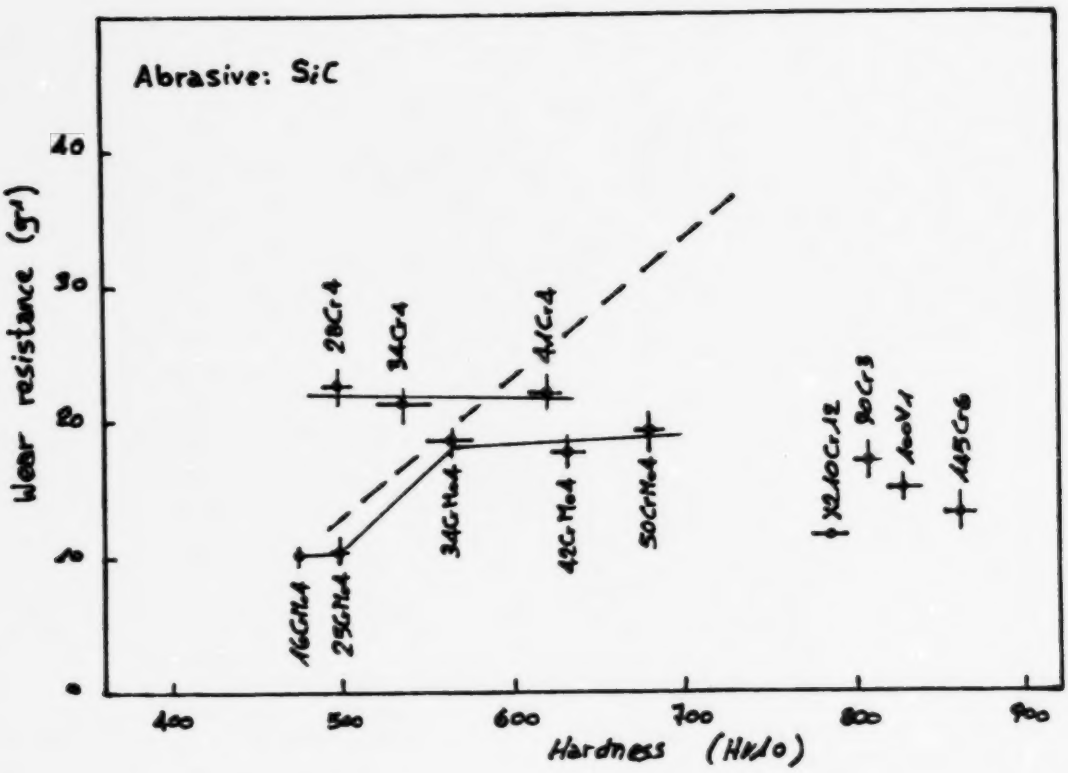


Fig. 21 Resistance to wear by SiC of the alloy steels hardened and tempered at 180°C plotted against the bulk hardness.

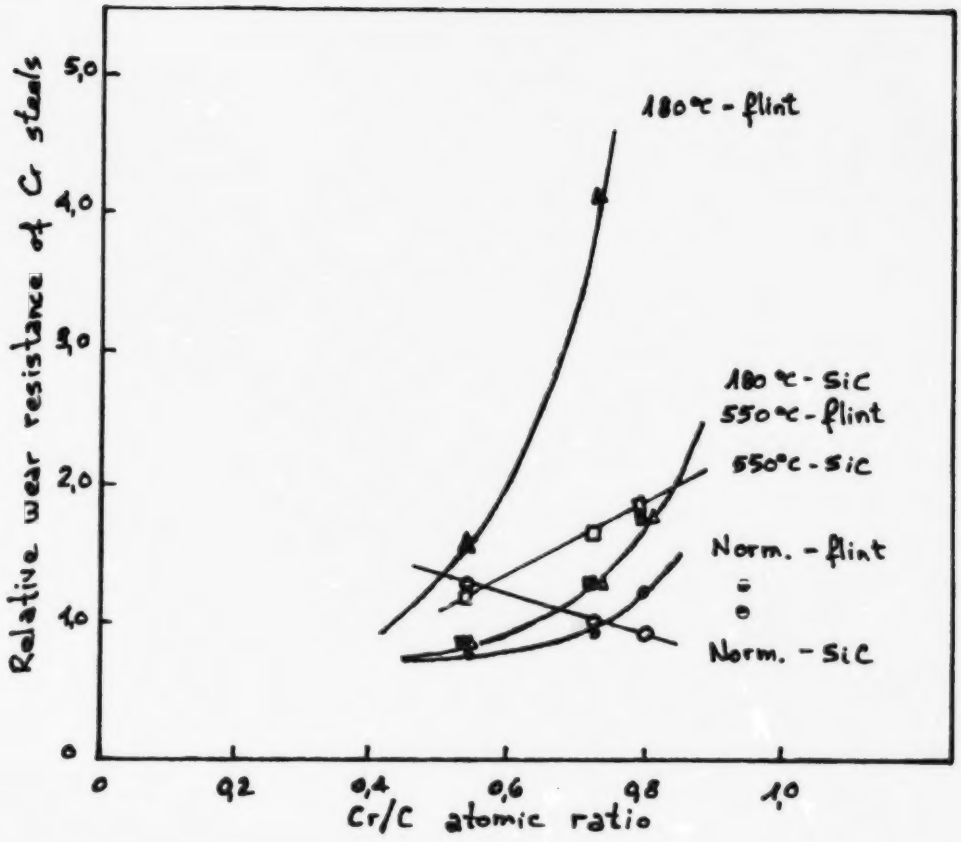


Fig. 22 Relative wear resistance of the chromium steels plotted against the chromium-to-carbon atomic ratio.

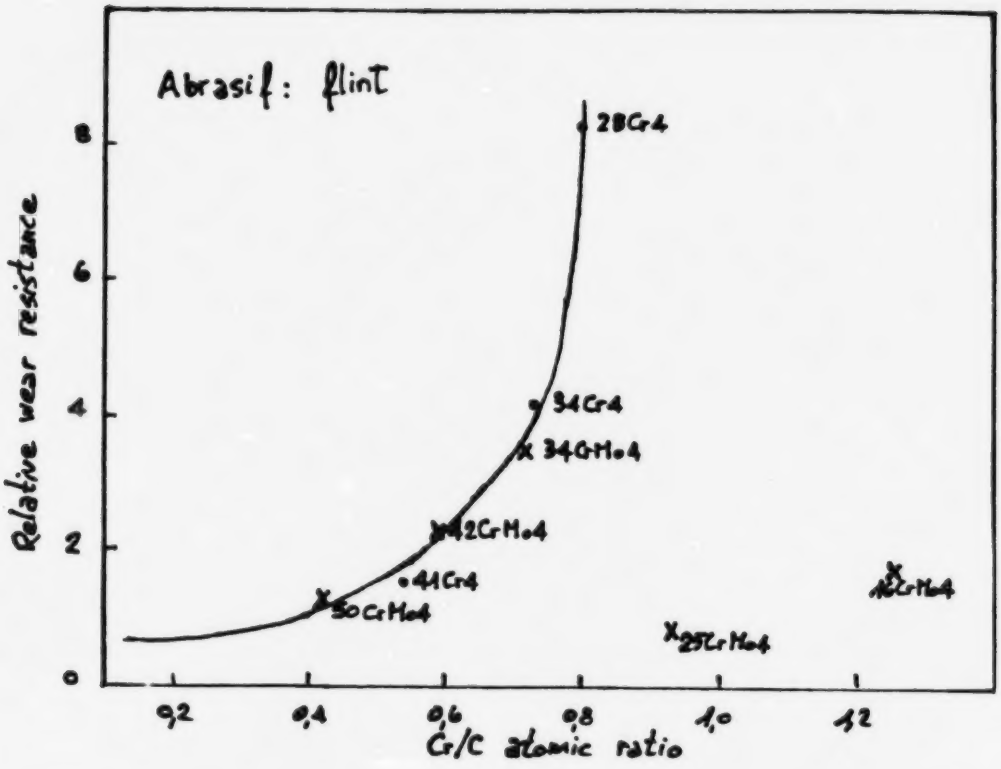


Fig. 23a Relative resistance to wear by flint of the chromium-molybdenum steels hardened and tempered at 180°C, plotted against the chromium-to-carbon atomic ratio.

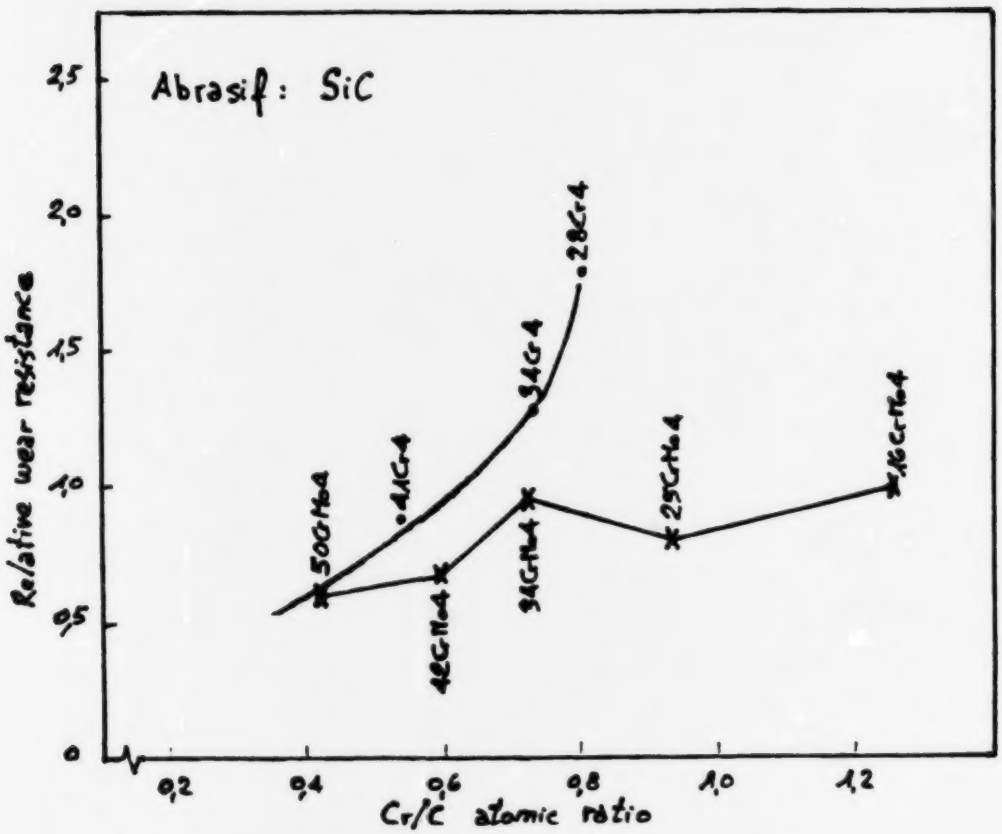
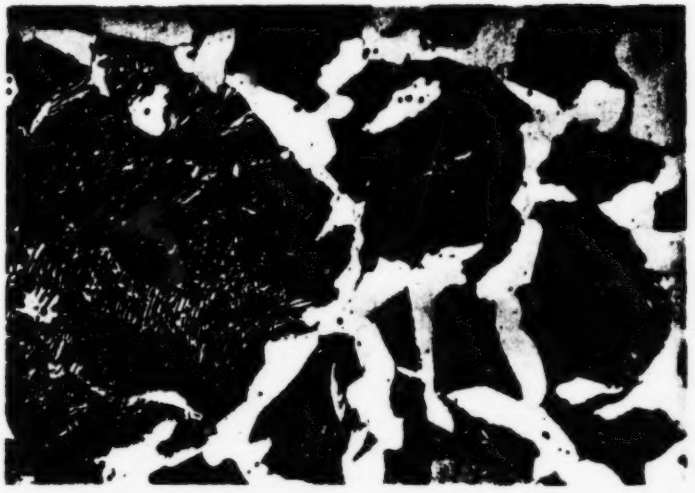


Fig. 23b Relative resistance to wear by silicon carbide of the chromium-molybdenum steels hardened and tempered at 180°C, plotted against the chromium-to-carbon atomic ratio.

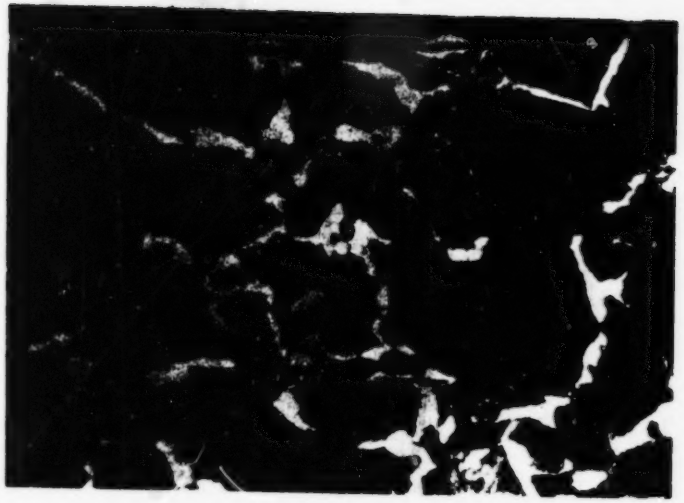
A1 C15 (AISI 1015), normalized

A2 Ck22 (AISI 1020), normalized

A3 Ck35 (AISI 1035), normalized



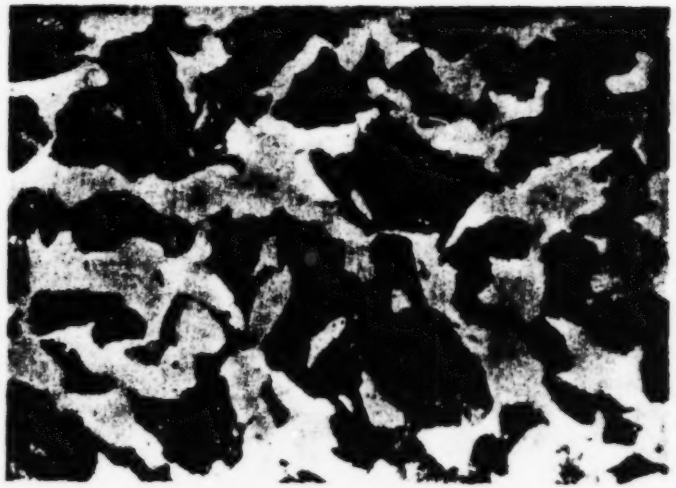
A4 C45 (AISI 1045), normalized



A5 Ck53, normalized

A6 C60 (AISI 1060), normalized

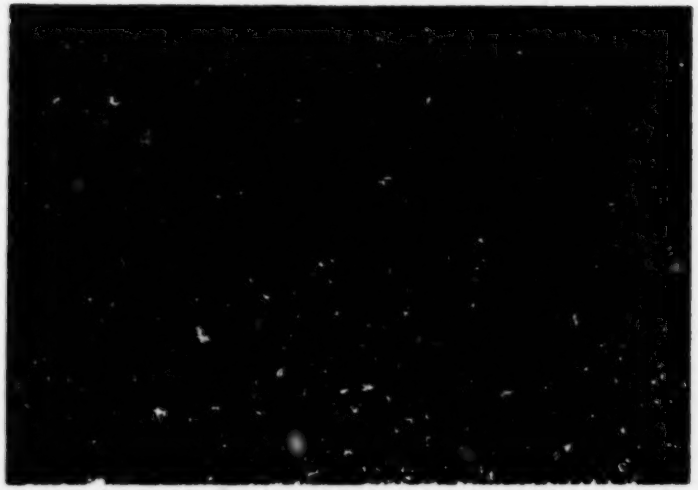
A7 15Cr3 (AISI 5015), normalized



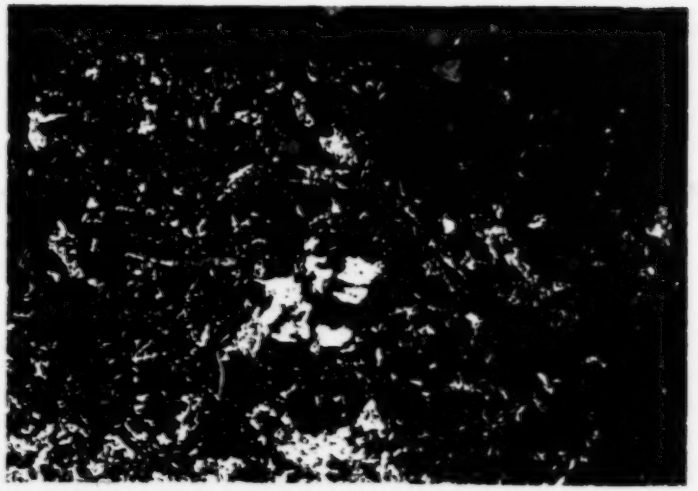
A8 28Cr4, normalized

A9 34Cr4 (AISI 5132), normalized

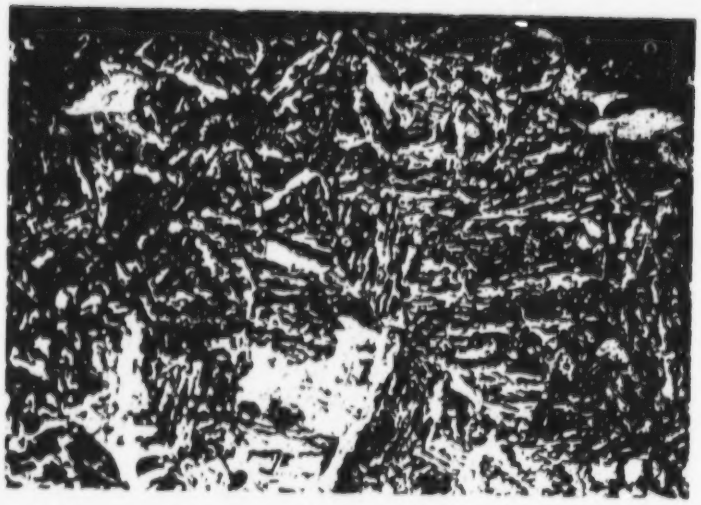
A10 41Cr4 (AISI 5140), normalized



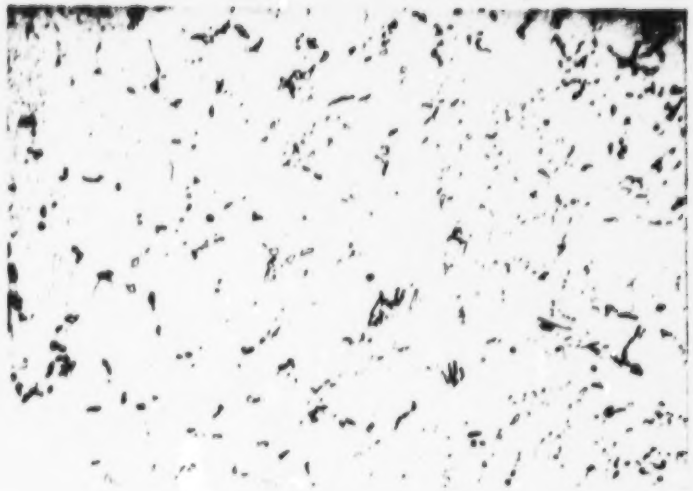
A11 34CrMo4 (AISI 4137), normalized



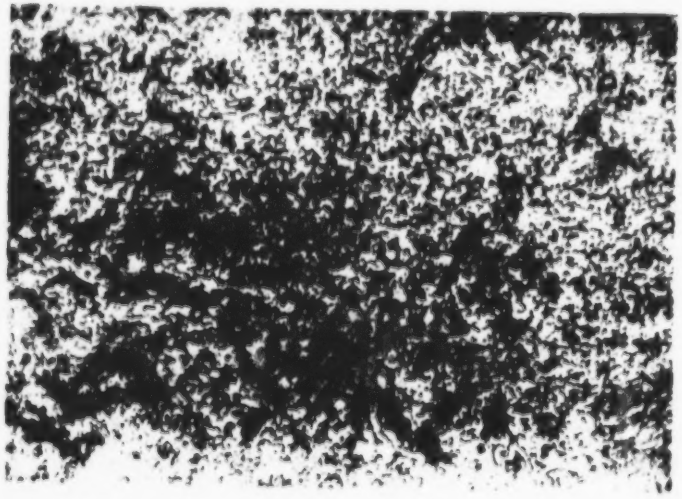
A12 42CrMo4 (AISI 4140), as received



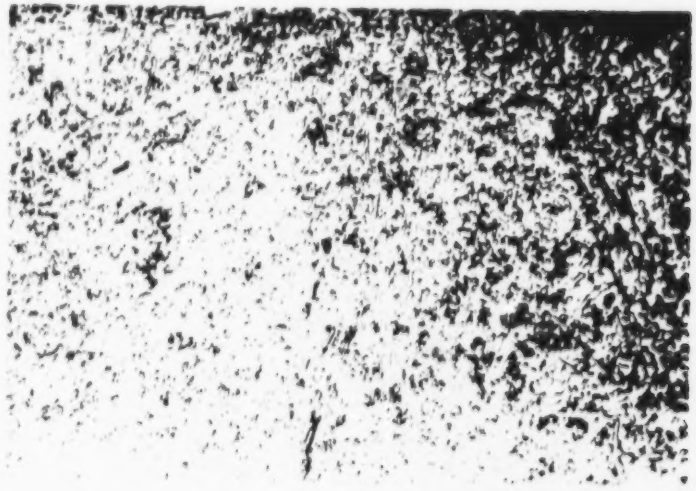
A13 50CrMo4, as received



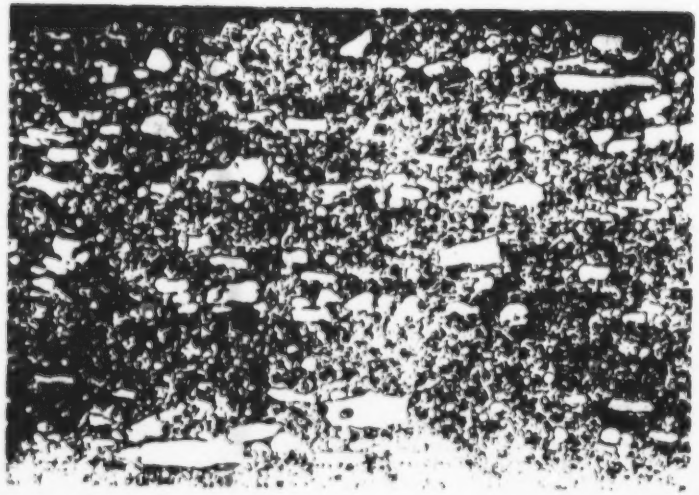
A14 90Cr3, spheroidized



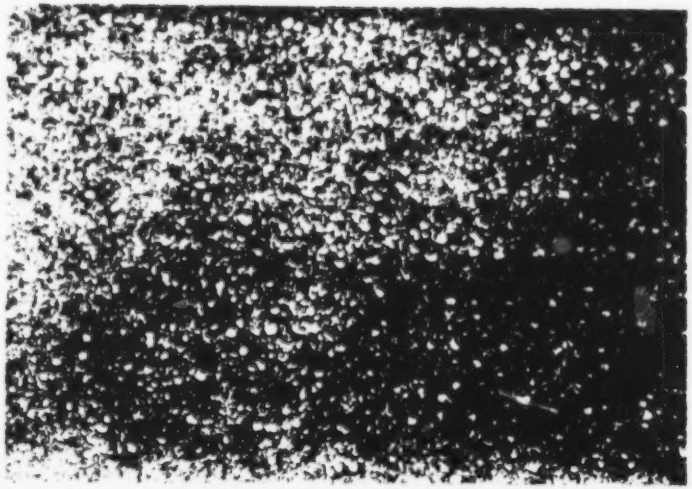
A15 100V1 (AISI W210), spheroidized



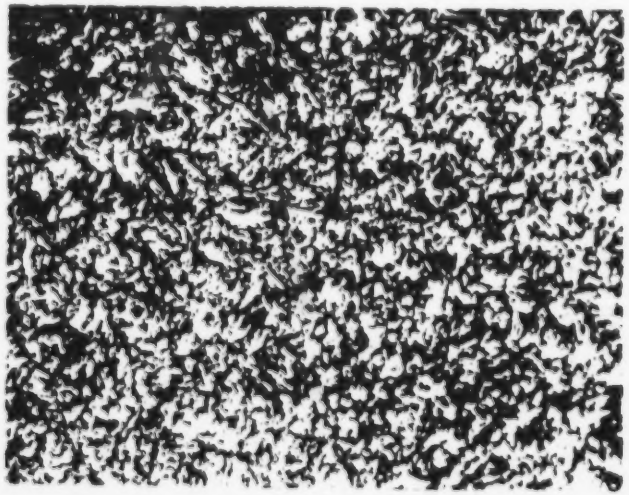
A16 145Cr6, spheroidized



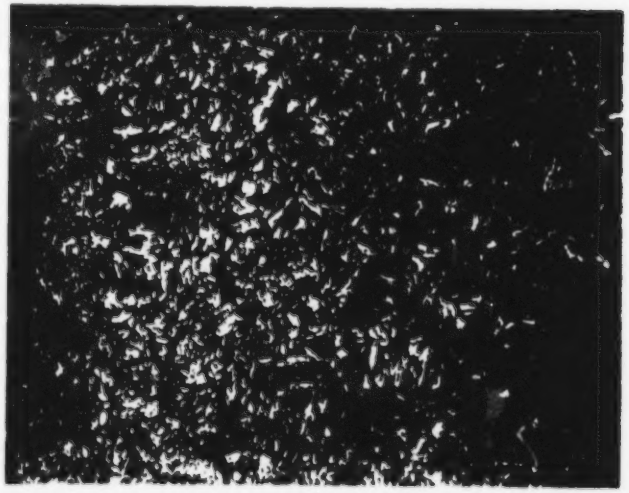
A17 X210Cr12 (AISI D3), spheroidized



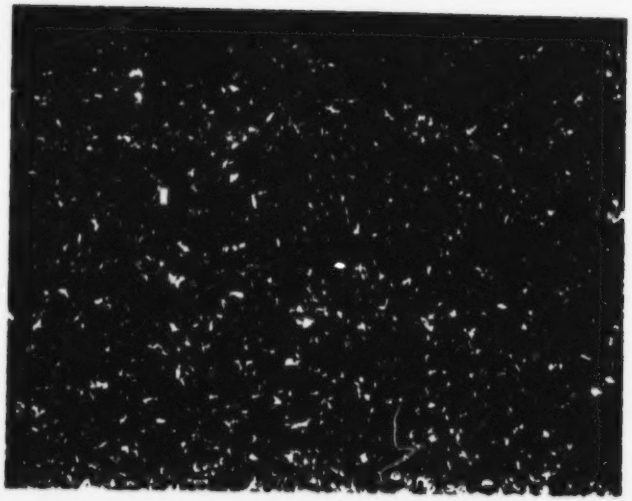
A18 S6-5-2 (AISI M2), spheroidized



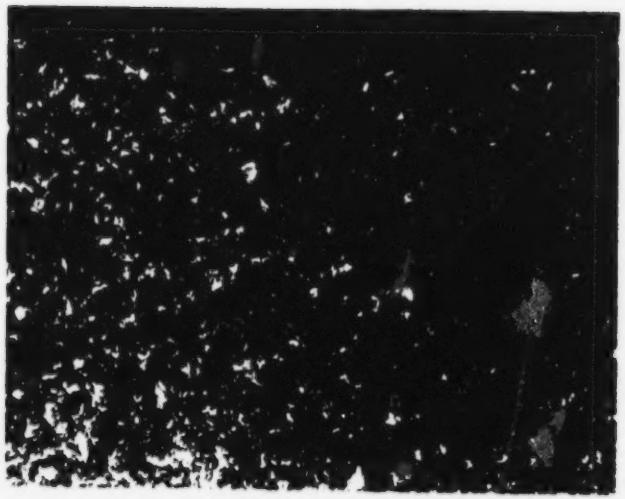
A19 Ck22 (AISI 1020), hardened
and tempered at 550°C



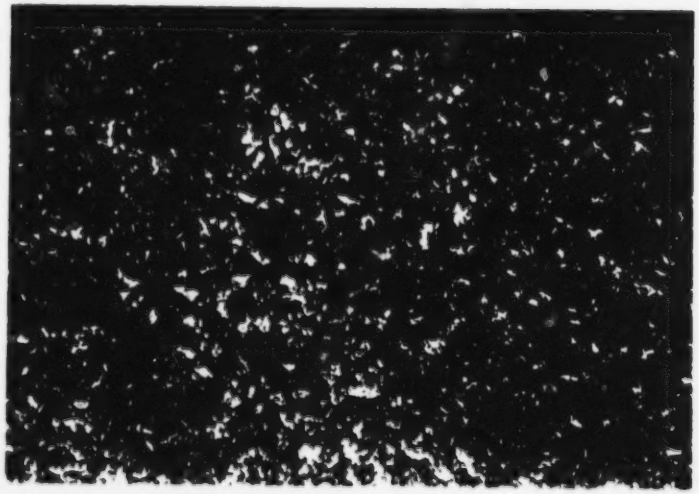
A20 Ck35 (AISI 1035), hardened
and tempered at 550°C



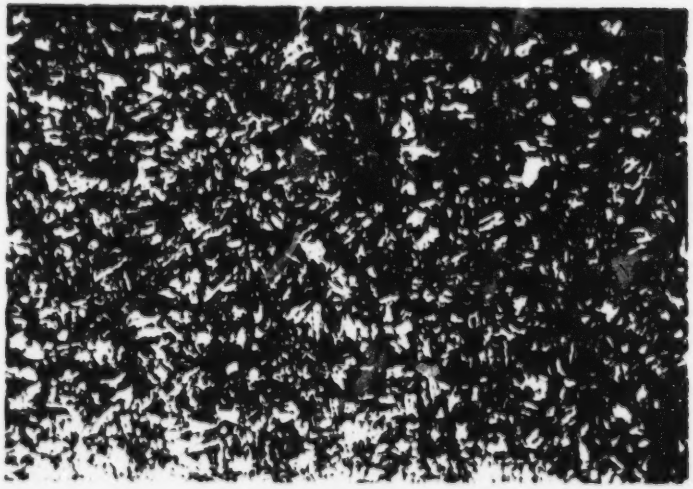
A21 C45 (AISI 1045), hardened and tempered at 550°C



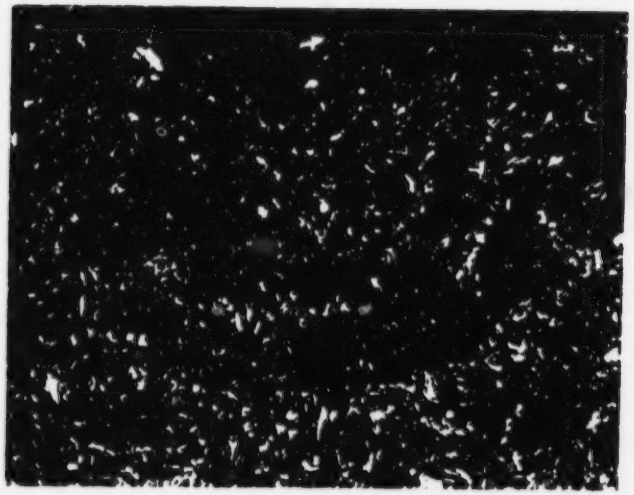
A22 Ck53, hardened and tempered at 550°C



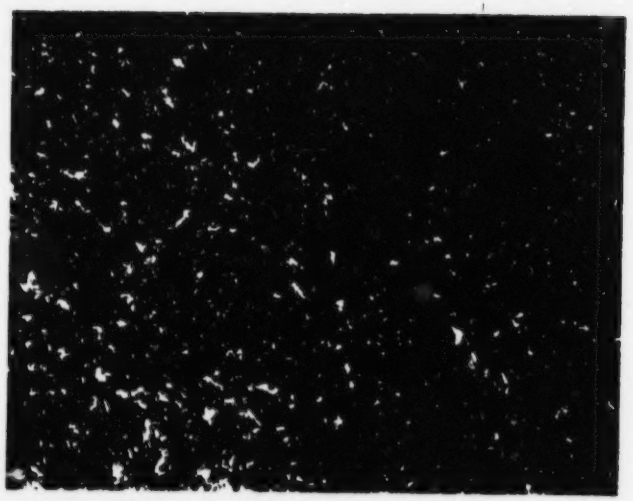
A23 C60 (AISI 1060), hardened and tempered at 550°C



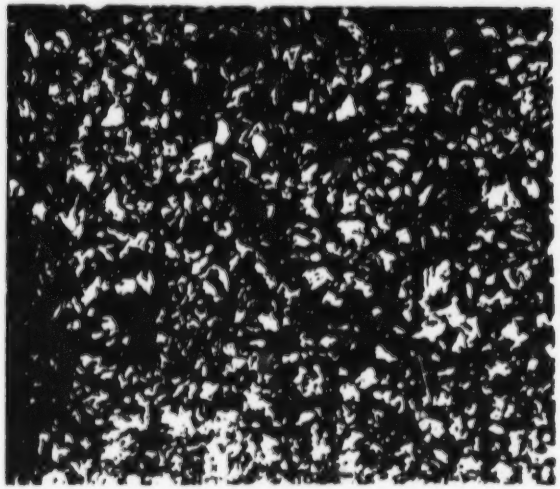
A24 28Cr4, hardened and tempered at 550°C



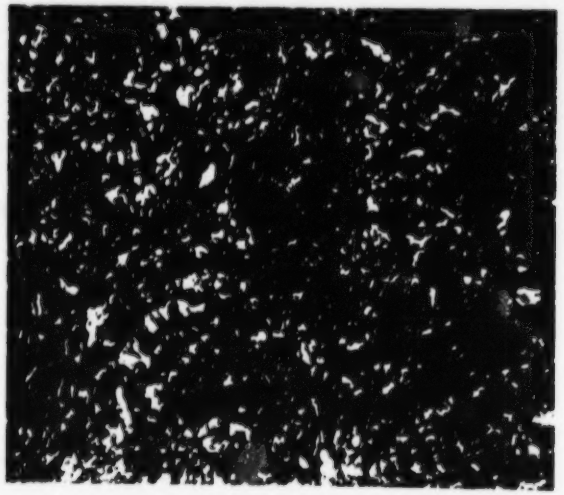
A25 34Cr4 (AISI 5132), hardened and tempered at 550°C



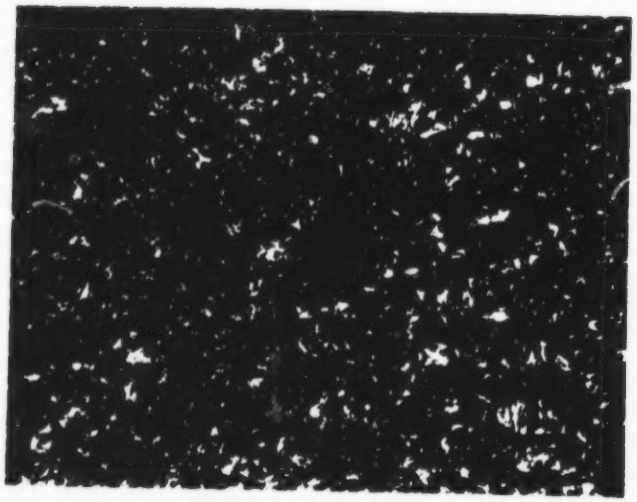
A26 41Cr4 (AISI 5140), hardened and tempered at 550°C



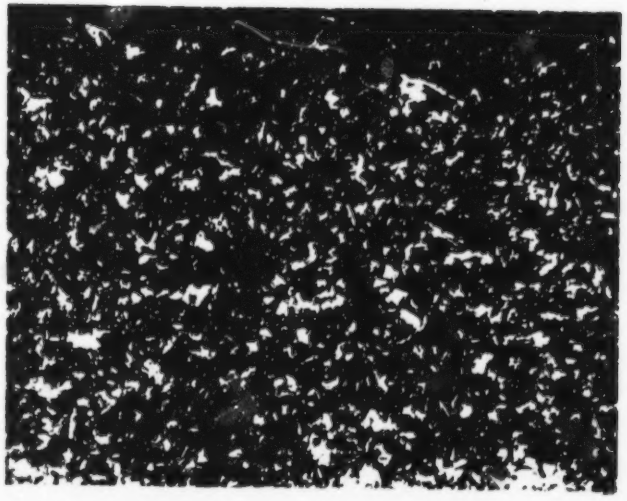
A27 16CrMo4, hardened and tempered at 550°C



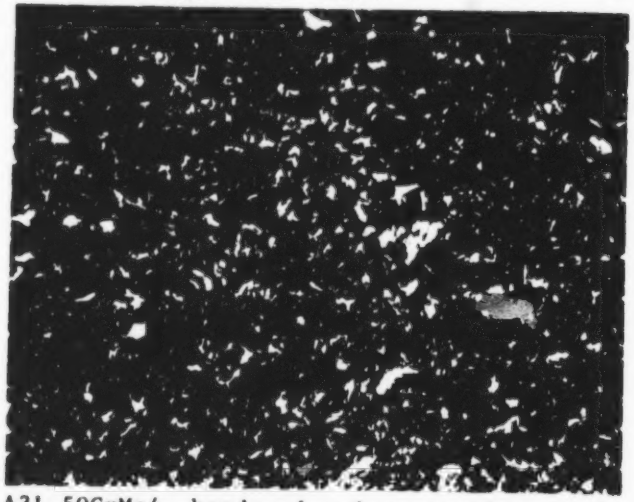
A28 25CrMo4, hardened and tempered at 550°C



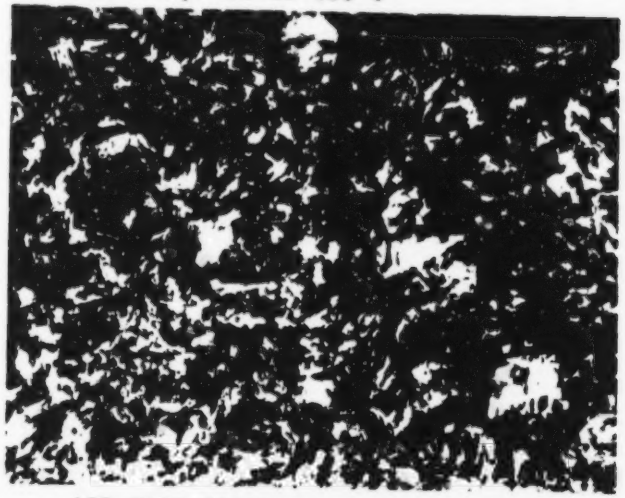
A29 34CrMo4 (AISI 4137), hardened and tempered at 550°C



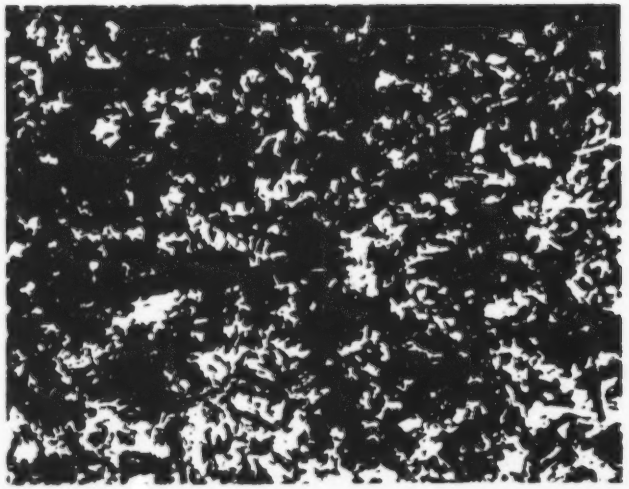
A30 42CrMo4 (AISI 4140), hardened and tempered at 180°C



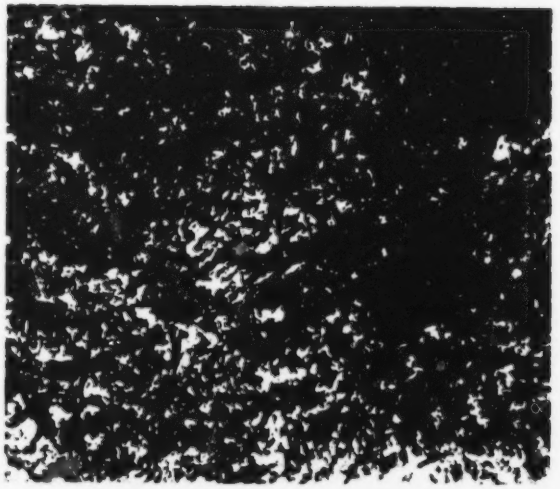
A31 50CrMo4, hardened and tempered at 550°C



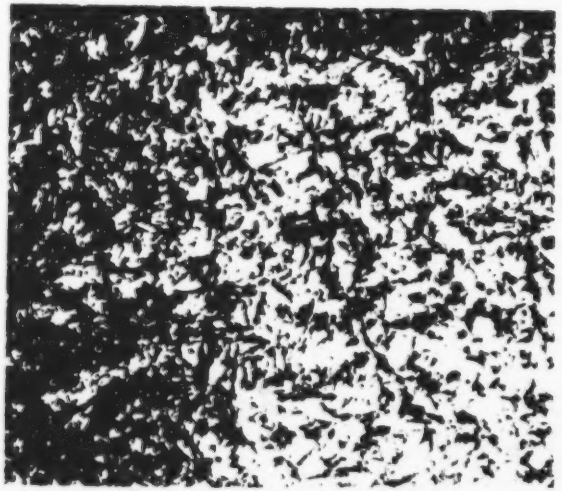
A32 Ck22 (AISI 1020), hardened and tempered at 180°C



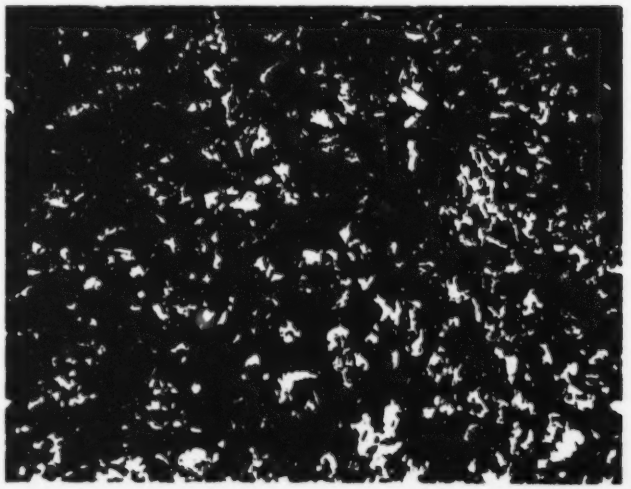
A33 Ck35 (AISI 1035), hardened and tempered at 180°C



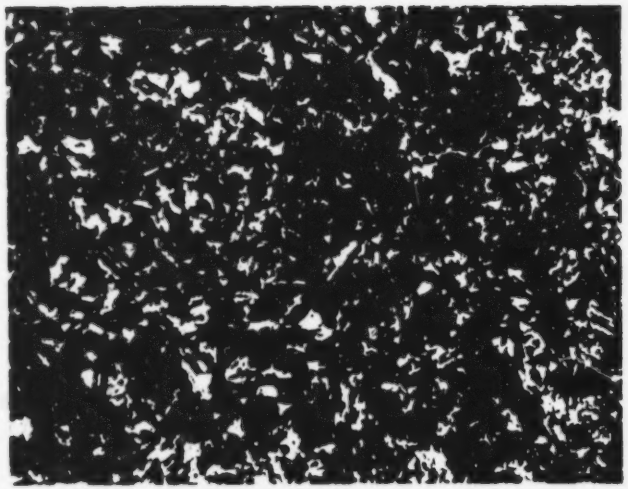
A34 C45 (AISI 1045), hardened and tempered at 180°C



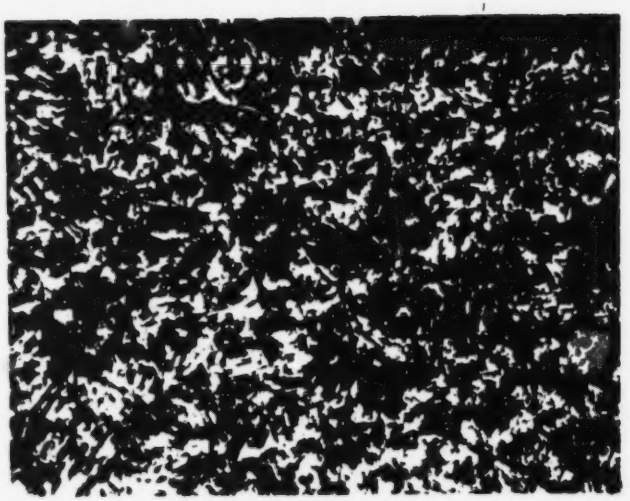
A35 Ck53, hardened and tempered at 180°C



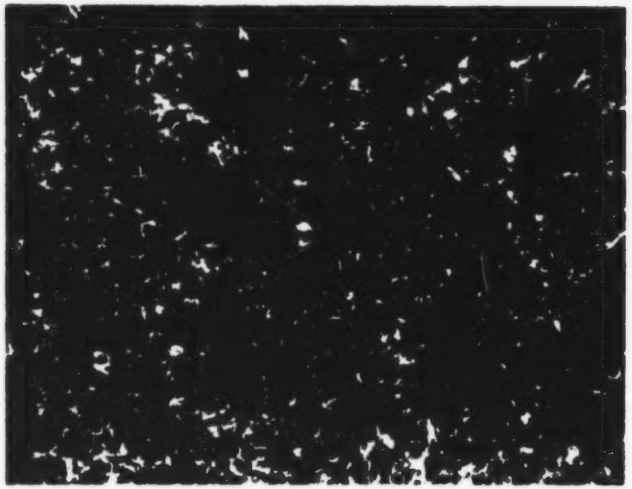
A36 C60 (AISI 1060), hardened and tempered at 180°C



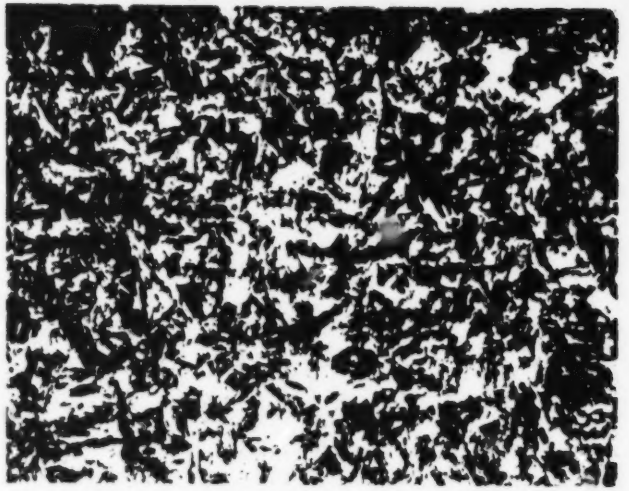
A37 28Cr4, hardened and tempered at 180°C



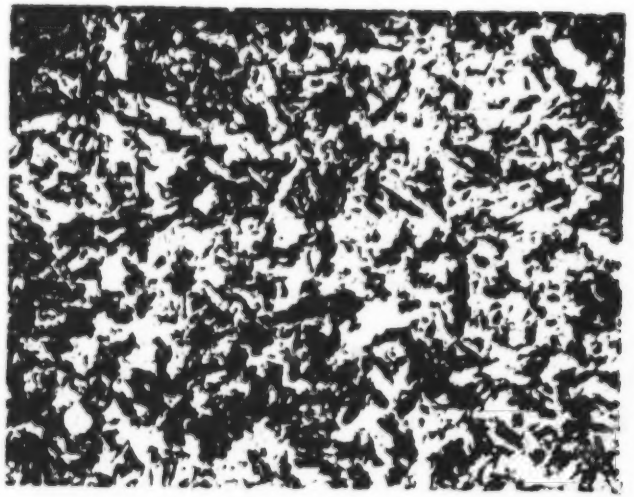
A38 34Cr4 (AISI 5132), hardened and tempered at 180°C



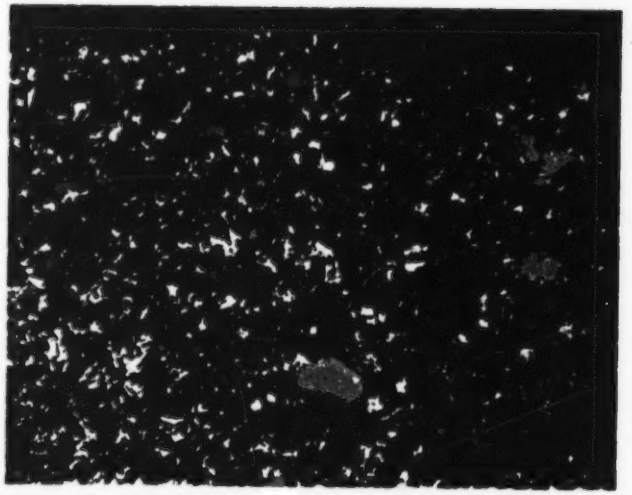
A39 41Cr4 (AISI 5140), hardened and tempered at 180°C



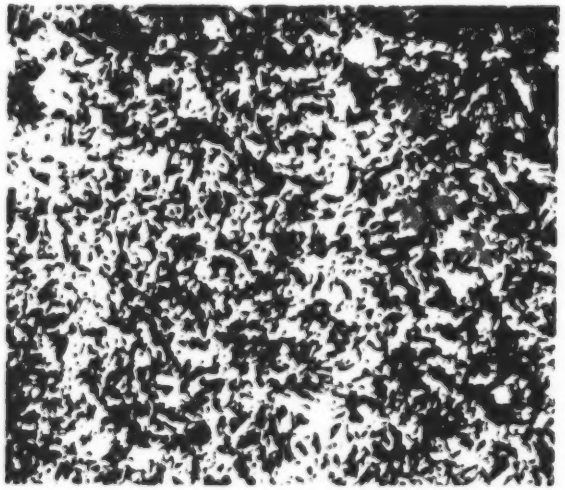
A40 16CrMo4, hardened and tempered at 180°C



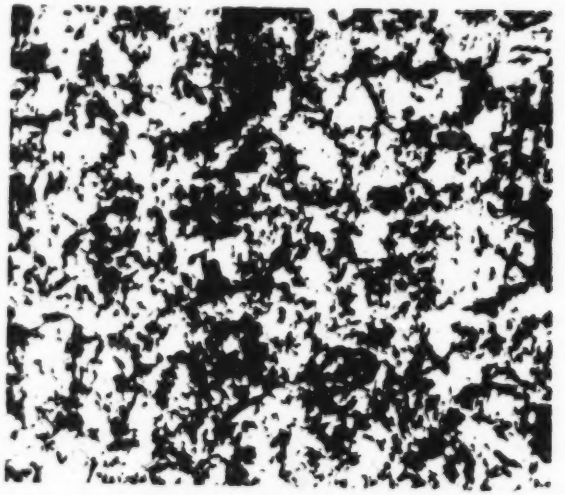
A41 25CrMo4, hardened and tempered at 180°C



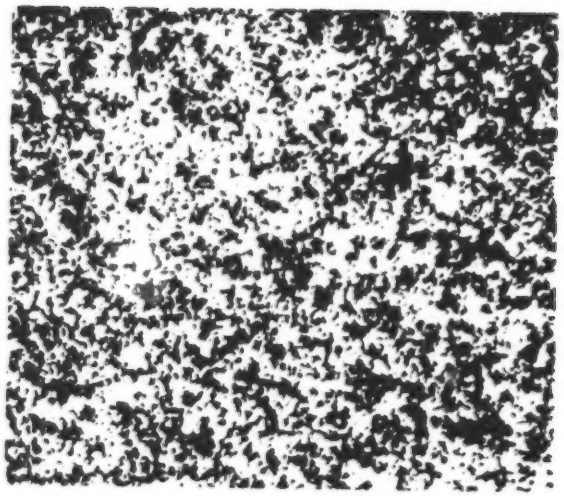
A42 34CrMo4 (AISI 4137), hardened and tempered at 180°C



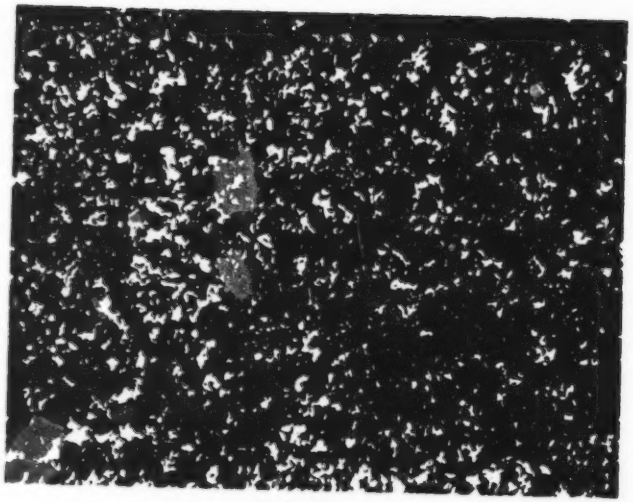
A43 42CrMo4 (AISI 4140), hardened and tempered at 180°C



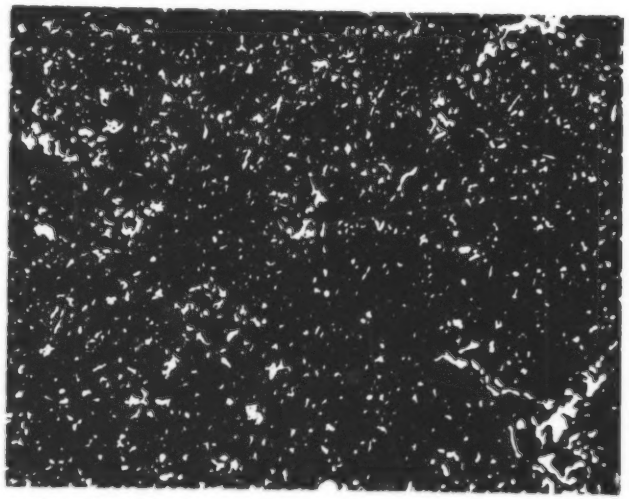
A44 50CrMo4, hardened and tempered at 180°C



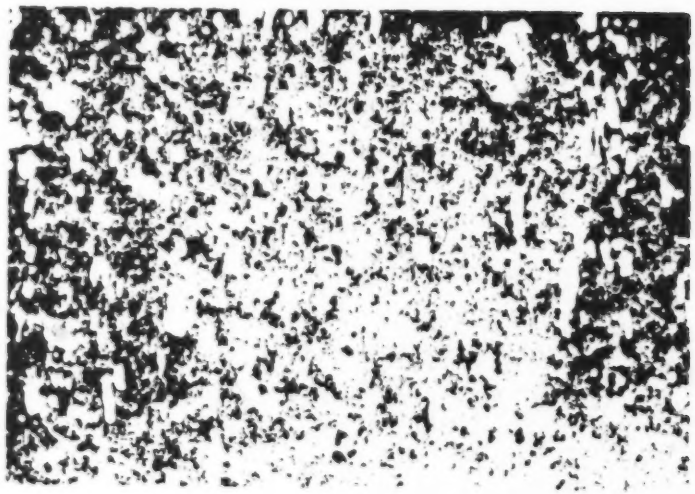
A45 90Cr3, hardened and tempered at 170°C



A46 100V1 (AISI W210), hardened and tempered at 170°C



A47 145Cr6, hardened and tempered at 170°C



A48 X210Cr12 (AISI D3), hardened and tempered at 200°C